AN OCEANOGRAPHIC INVESTIGATION OF THERMAL CHANGES IN MONTEREY BAY, CALIFORNIA SEPTEMBER 1971 - JANUARY 1972

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THESIS

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by

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An Oceanographic Investigation of Thermal Changes

in Monterey Bay, California

September 1971 - January 1972

by

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Lieutenant, United States Coast Guard
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from the

ABSTRACT

Nine oceanographic stations in Monterey Bay were occupied on at least weekly intervals from 21 September 1971 through 28 January 1972. During this period the three oceanic seasons described by previous investigators were observed. Measured thermal conditions were compared to previously derived long-term mean values. The magnitude of the short-period thermal fluctuations was comparable to that noted in earlier investigations. The changes in seasonal thermal structure were greater and more rapid than climatology implied. Unusually weak upwelling in August 1971 was followed in October by stronger than normal upwelling. This resulted in an interruption in the Oceanic Period and delayed the start of the Davidson Current regime in the bay.

The network of regularly occupied stations was more extensive than had been previously possible. Quasi-synoptic observations between two offshore stations indicated north-south geostrophic current velocity components on the order of 2 to 14 cm/sec.

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The author wishes to express his thanks to Mr. Jerrold Norton of the Department of Oceanography, Naval Postgraduate School, for his assistance in collecting and processing data.

Special praise is due Mr. W. W. Reynolds, Master, R/V ACANIA; Mr. Bob Winton, Chief Engineer; and Mr. Steve Bliss, First Mate, for their cooperation during the data colelction phase of this research. The professional skill and "Will Do" attitude of these men helped to make the necessary field work both effective and pleasant.

I. INTRODUCTION

A. OBJECTIVES

The oceanographic study reported in this paper was unusual in that while the observation period was only a third of a year in duration, September 1971 through January 1972, it spanned what might be the most interesting portion of the annual series of changes occuring in the waters of Monterey Bay. Of interest was the observation of the generally recognized upwelling period at the beginning and end of the study and of the previously described Oceanic and Davidson Current Periods.

This investigation was also different from other Monterey Bay studies with regard to the number of points of observation and the location of these points. Nine stations, which could be covered on a one day cruise were selected so as to give a reasonably close net over the Monterey Canyon. While this number of stations is generally greater than used by previous investigators, the net was designed to include observations near some points used previously. Although most of the stations were concentrated over the axis of the canyon, the northern and southern shallow regions of the bay were represented with two stations each. Stations 2 and 3 were chosen on an east-west line off Pt. Pinos in order to determine the north-south current velocity components offshore between these stations to a depth of approximately 950 meters.

The nine stations were visited on at least a weekly basis over the period of the study.

The objectives of this research were:

1. to determine, by comparison with the results obtained by Lammers (1971), whether or not the conditions in the bay were "normal," and to seek explanation for anomalous behavior;
2. to find out if it was possible or reasonable to quantitatively describe the vertical thermal gradients which differentiate the cyclic regimes within Monterey Bay;
3. to relate the offshore currents as observed between Stations 2 and 3 to the changes within Monterey Bay; and
4. to expand the collection of useful oceanographic Monterey Bay data.

B. PREVIOUS RESEARCH

During the five-year interval 1929-33, Skogsberg (1936) carried out oceanographic observations at 23 stations in the canyon and southern shallow areas of Monterey Bay, at different times. As a result of these observations an annual rhythm of thermal characteristics is described for the bay. From the latter part of August through most of October relatively warm waters in the upper 25-50 meters are attributed to the proximity to the coast of the California Current. The Davidson Current, driven by prevailing southerly winds, causes a low thermal

gradient and relatively high temperatures in the upper 50-100 meters over the months of December, January, and the first part of February. Upwelling occurs from the middle of February to the end of November and is indicated by the presence of the 9°C isotherm above 100 meters.

Skogsberg noted that, while there was a narrow range of long period thermal variation (6.5°C at the surface for the five-year period), the rate of thermal change was relatively great even on an hourly basis. Also the transition between the thermal regimes was not uniform, but was interrupted by apparently random fluctuations bringing thermally different water masses into the bay. The annual rhythm was disturbed by the sporadic influx of waters from the California Current and by wind-driven changes in the near-surface circulation. The effects of insolation and radiation upon the thermal structure of the area were relatively minor as compared to the sub-surface advection processes.

Sverdrup and Fleming (1941) reported that the upwelling waters rose from less than 200 m. and represent an "overturning" of the upper layers. Also a countercurrent of Equatorial Water flows near the coast at depths greater than 200 m. during the upwelling period. Throughout the intense upwelling, tongues of cold water move to the south and away from the coast and are interspersed with tongues of warmer water moving northward and toward the coast. As the intensity of the upwelling decreases in late summer these flows of cool and warmer water degenerate into irregular eddies. Some

eddies cause water to be transported away from the coast while others move surface layer oceanic water to the coast resulting in the Oceanic Regime described by Skogsberg.

With the decrease in upwelling the Davidson Current, a northward wind-driven surface countercurrent, develops and flows in conjunction with the subsurface countercurrent on the coastal side of the California Current. The effect of the upwelling, then, is to disrupt the surface countercurrent, and the implication is made (Sverdrup, et al., 1942) that if it were not for the prevailing winds causing the upwelling the countercurrent would persist at all depths.

Bolin and collaborators (1964) conducted weekly hydrographic observations of a single station at 36°42'N, 122°02'W from January 1951 through December 1955 and provide some refinement to the descriptions of the three regimes as given by Skogsberg. During the months of March, April, and May a surface temperature of 10 or 11°C is normal with no clearly developed sea surface temperature gradients present. Upwelling generally ends by September although periods of northwest winds cause short periods of upwelling as late as November. The oceanic phase exhibits a thin layer of warm water near the surface with a normal surface temperature of 13°C and a sharp, shallow thermocline. With the onset of the Davidson Current the sea surface temperatures are slightly lower. A shoreward mass transport depresses the thermocline to between 50 and 100 meters and causes the

small thermal gradient characteristic of the surface layers of this period.

Lammers used an IBM 360 computer to compile the data gathered by Skogsberg (1929-1933), Bolin (1951-1955) and the CalCOFI (1954-1967) cruises. These data were applied to 19 four-mile squares arranged over Monterey Bay. Data collected anywhere within a given square was, for the purpose of that study, assumed to come from the center of the square. This assumption, coupled with the scarcity of data available in some blocks, and the frequent long time periods between collections of data, caused problems which were reported by the author. However, this was the first effort at deriving norms for the thermal characteristics of the entire bay over an extended period of time, and as such made it possible to determine whether or not the thermal properties of a specific period of time were anomalous. Lammers notes a progressive warming of the upper 100 meters and a decrease in the intensity of upwelling over the 40-year interval. Also the presence of a relative warm surface layer pool over the canyon axis implies an anticyclonic circulation under approximately geostrophic conditions.

Anderson (1971) compared synoptic sets of available data collected during the periods September 1966 through September 1967 (Period I) and January 1970 through June 1971 (Period II) to the norms established by Lammers. The parameters used were the sea surface temperature, the temperature at the 20-meter isobath, and the depths of the 9°C and

10°C isotherms. During Period I the three seasonal regimes were normal but during Period II a more intense upwelling period was preceded by a warmer than normal Davidson Current period and followed by an abnormally cooler Oceanic Period.

While the studies of Lammers and Anderson were carefully prepared, they were based upon other investigators' data collected over diversified periods of time from not always consistent locations. Furthermore, no study had been designed to concentrate on the Oceanic and Davidson Current Periods in Monterey Bay. The requirement existed, then, for a series of observations to be repeated at at least weekly intervals at a series of carefully selected stations in the bay over the months of September through January. This paper reports on research conducted to fulfill the above requirement.

C. DESCRIPTION OF AREA OF STUDY

Monterey Bay is a nearly semi-elliptical indentation of the California coastline having its major axis of approximately 22 nautical miles oriented in a north-south direction at about 121°55'W. Its east-west minor axis is roughly 10 nautical miles in length and is centered at about 36°48'N.

The 100-meter isobath delineates the broad northern shallows and smaller southern shallows from the steep slope of the Monterey Canyon. This canyon, the depth of which exceeds 2,000 meters less than ten miles from the city of Monterey, results in the bay having readily available deep water oceanic features.

Although it was necessary to assume that each cruise produced synoptic observations, it was obvious that considerable fluctuations in, for example, isotherm depth occurred within periods of one to three hours. The only way to really approach synoptic observations would be through the coordinated use of aircraft and anchored instrument arrays, or of two or more ships. Neither approach was practical over the short time span of this research.

II. PROCEDURE

A. DATA COLLECTION

The acquisition of the Research Vessel ACANIA by the Naval Postgraduate School, to replace a 63-foot hydrographic research boat, considerably extended the cruise radius and increased the logistical support and platform capabilities for marine studied by the Department of Oceanography. It is doubtful that the data collection necessary for this study would have been possible with the previously available boat. There was no doubt, however, that the sea-keeping qualities of ACANIA and the energy of her three man civilian crew made the hours of data collection by far the most pleasant part of this research.

Data for this study was obtained during 23 cruises conducted from 21 September 1971 through 28 January 1972, using approximately 218 hours of ship time. Four hundred thirty-eight sea-surface bucket temperature observations and 288 mechanical bathythermograph and XBT drops were made. In addition 31 Nansen casts and 24 STD casts were carried out.

Cruises for this project were executed at, for the most part, weekly intervals sequentially around the nine stations in the bay as shown on Figure 1.

Sea surface temperature measurements were made at each station and at the half-way point between stations. BT drops were made at each station and half way between

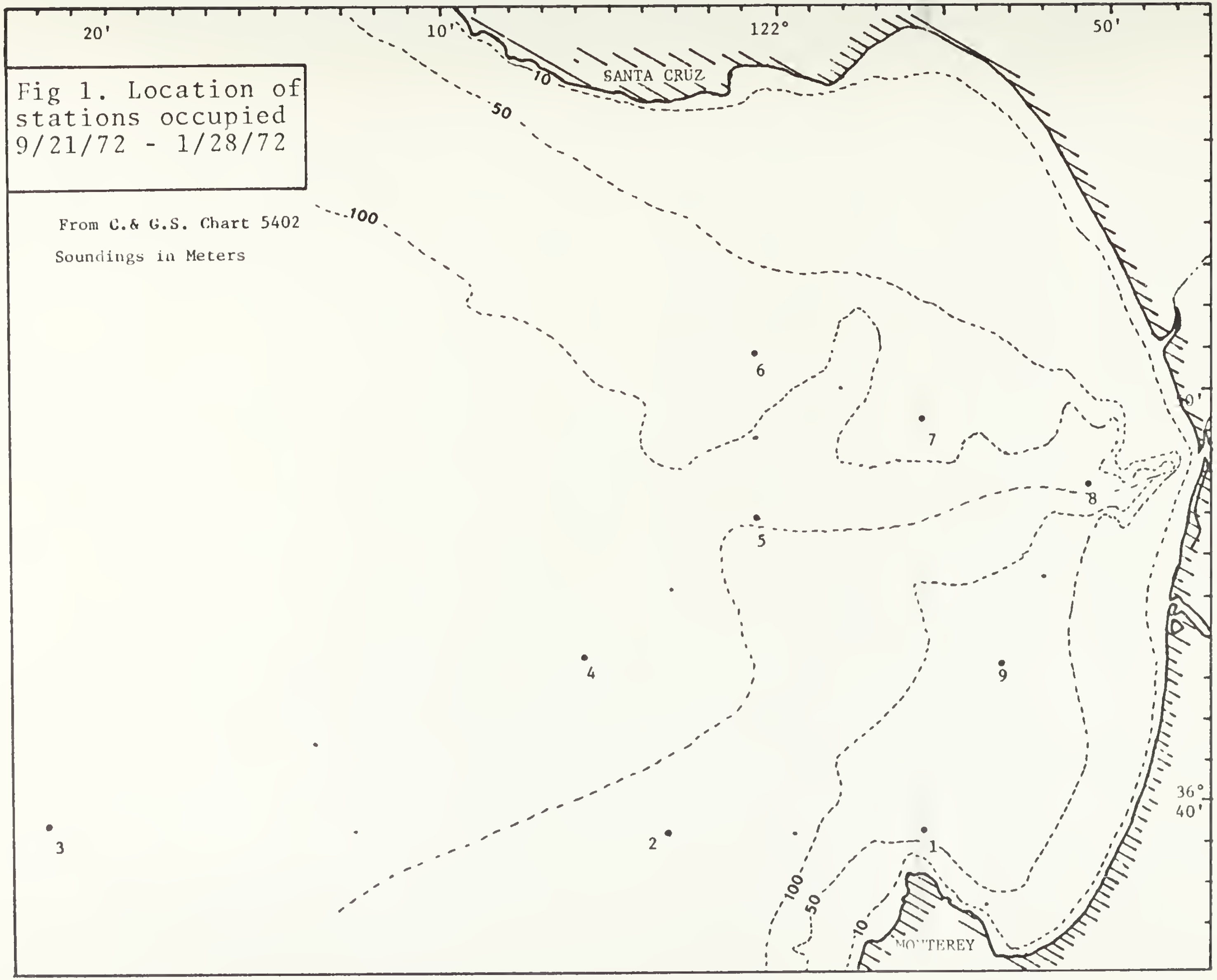

Fig 1. Location of stations occupied 9/21/72 - 1/28/72

From C.& G.S. Chart 5402

Soundings in Meters

Stations 2 and 3, and Stations 3 and 4. Nansen casts and/or STD casts were carried out at Stations 2 and 3 in an attempt to describe the north-south current components between these stations.

Bathythermograph drops were made with both 200 and 900 foot mechanical BT's and with 1500 foot Sippican expendable BT's.

Nansen casts were made with 10 bottles to a depth of 1,000 meters. A Bisset-Berman salinity-temperature-depth probe (STD) with a self-contained magnetic tape recorder was used as a source of additional information.

III. RESULTS

A. SYNOPSIS OF CALIFORNIA COASTAL OCEAN TEMPERATURE CONDITIONS FROM AUGUST 1971 THROUGH DECEMBER 1971

Anomalously low sea surface temperatures from Baja California to Vancouver Island in July were replaced by unusually high values during the first half of August (Ref. 1). A northwest displacement of the northeastern Pacific anticyclone caused a weak atmospheric pressure gradient along the coast and allowed a weakening of the upwelling which normally leads to cooler coastal surface waters.

California coastal waters south from Point Arena to Baja California continued to warm during the first part of September and stayed warm during the rest of the month as a result of the reduced upwelling. October was characterized by an unusually high pressure area centered at about 37°N and 143°W. This anticyclone generated strong northerly winds along the West Coast which drove a southward transport of cold water, increased upwelling and evaporation, and caused rapid coastal cooling. The high which prevailed in October continued in November to produce strong north and northeast winds which maintained the southward advection of cold water and upwelling. During December the northeastern Pacific high pressure area moved to the northwest and intensified causing stronger than normal winds along the California coast and increased advection of waters from the north.

The National Marine Fisheries Service (NMFS) at Monterey and the Fleet Numerical Weather Central (FNWC) at Monterey routinely compute the offshore component of Ekman transport and from this produce a monthly coastal upwelling index at 36°N and 122°N. Through personal communication with Mr. A. Bakun at NMFS, the values for upwelling and the anomalies relative to the mean for the months from 1948 to 1967 were obtained for January 1971 through January 1972. The values shown below are for coastal upwelling in metric tons per second per kilometer of coastline.

MONTH	UPWELLING VALUE	ANOMALY	MEAN
Jan 1971	130	30	100
Feb	960	610	350
Mar	680	-120	800
Apr	2020	810	1210
May	2220	190	2030
Jun	2940	550	2390
Jul	2400	410	1990
Aug	1520	-310	1830
Sep	790	-150	940
Oct	730	240	490
Nov	250	130	120
Dec	70	0	70
Jan 1972	50	-60	110

In studying the values for the upwelling anomaly it is interesting to note the change in the values for July and August 1971. August shows the weakest upwelling for that month in ten years. September is also below average, but October and November show an unseasonal surge. This surge

was at least in part responsible for the prominent rise in the isotherms during the end of October and first part of November 1971. Further, it reveals an interesting consequence of the topography of Monterey Bay. The graphs of isotherm depth and sea surface temperature show that Station 8, at the head of the canyon, was particularly sensitive to this surge, and that after the surge the isotherms exhibited a very sharp increase in depth before resuming the decrease indicative of the season. Over the latter part of September (when this study began) the surface temperatures at Stations 8 and 6 were approximately 3.2°C higher than the average for all nine bay stations during the same period. This coincides with the reduced upwelling prevalent during that period. It is of interest to note that Station 6 was located on the northern shallows of the bay in close proximity to a prominent northern tributary of the main canyon. This increase in isotherm depth can be thought of as a sort of "rebound," and the magnified effect on the surge at the head of the canyon relative to the stations out in the deeper, wider portions of the canyons is reminiscent of water sloshing back and forth in a pitching, flat-bottomed boat. The rise and fall of free water in the pointed bow of the boat is much more obvious than in the wider, flatter stern.

Further examination of the upwelling figures show that the October 1971 surge was just a temporary deterrent in the rapid decrease in upwelling from the June maximum. The low upwelling values for November, December, and January are

presumably, in part a result of the Davidson Current. This northward flowing countercurrent would be expected to produce a decrease in the net flow which is southward along the coast, and this in turn would decrease the offshore transport responsible for the upwelling.

The Oceanic Period, a transition interval between the Upwelling and Davidson Current Periods, was less easy to define on the basis of the upwelling index values. Clearly the Oceanic Period was interrupted by the upwelling surge in October as the warmer surface waters became cooler and the thermal gradient in the upper 100 meters became less steep during the surge.

B. DAILY SEA SURFACE TEMPERATURES AT MONTEREY

Figures 2 through 7 show the daily changes in sea surface temperature for August 1971 through January 1972 as measured from Municipal Wharf No. 2, Monterey. Also shown for comparison are the average sea surface temperatures for the period beginning in 1966. It is seen that the sea surface temperature for August and September 1971 were above the five-year average, that October was approximately average, and that November, December 1971 and January 1972 were very much cooler than the average. The warm sea surface in August and September corroborates the above mentioned anomalously weak upwelling during the summer of 1971.

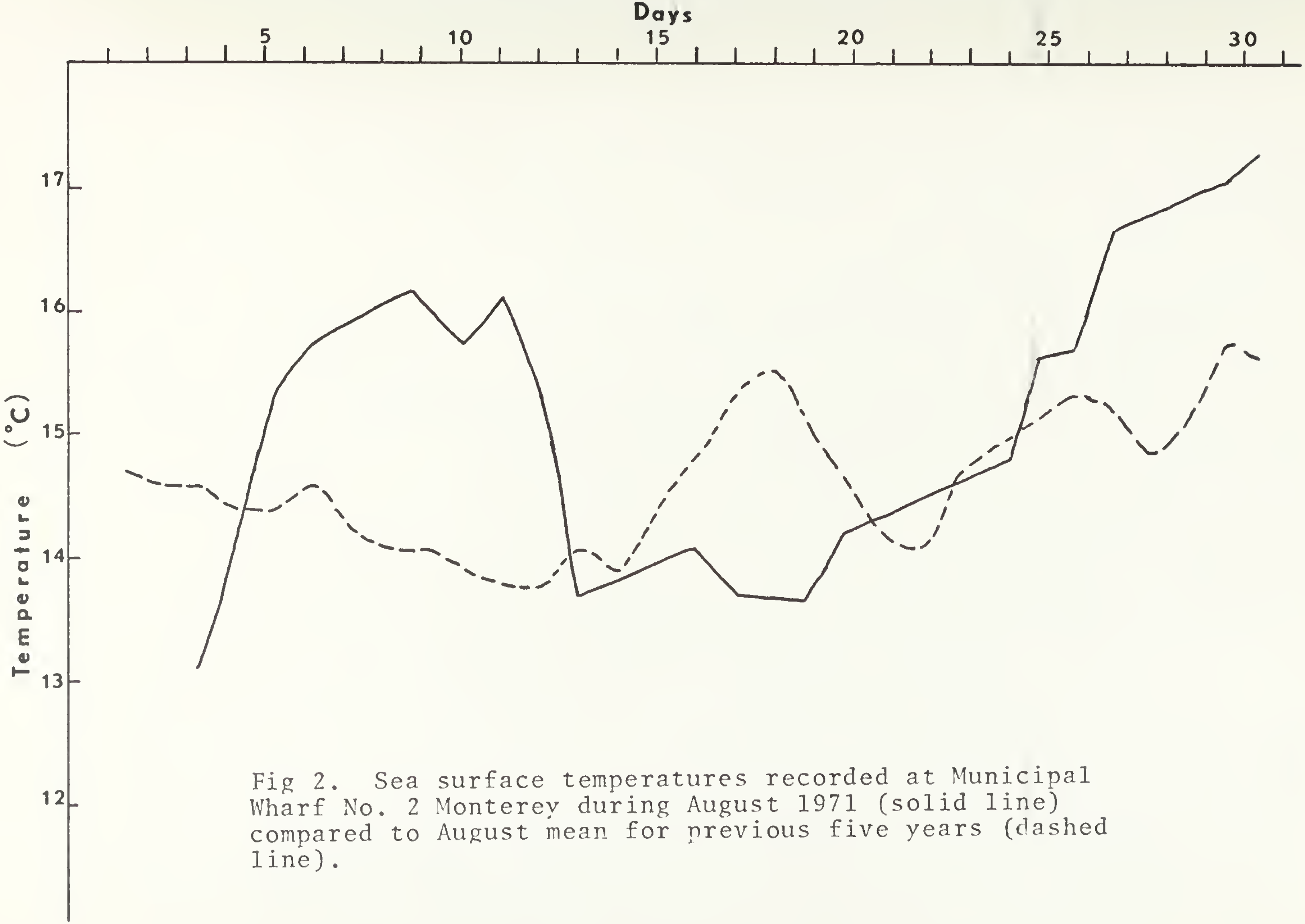

Fig 2. Sea surface temperatures recorded at Municipal Wharf No. 2 Monterey during August 1971 (solid line) compared to August mean for previous five years (dashed line).

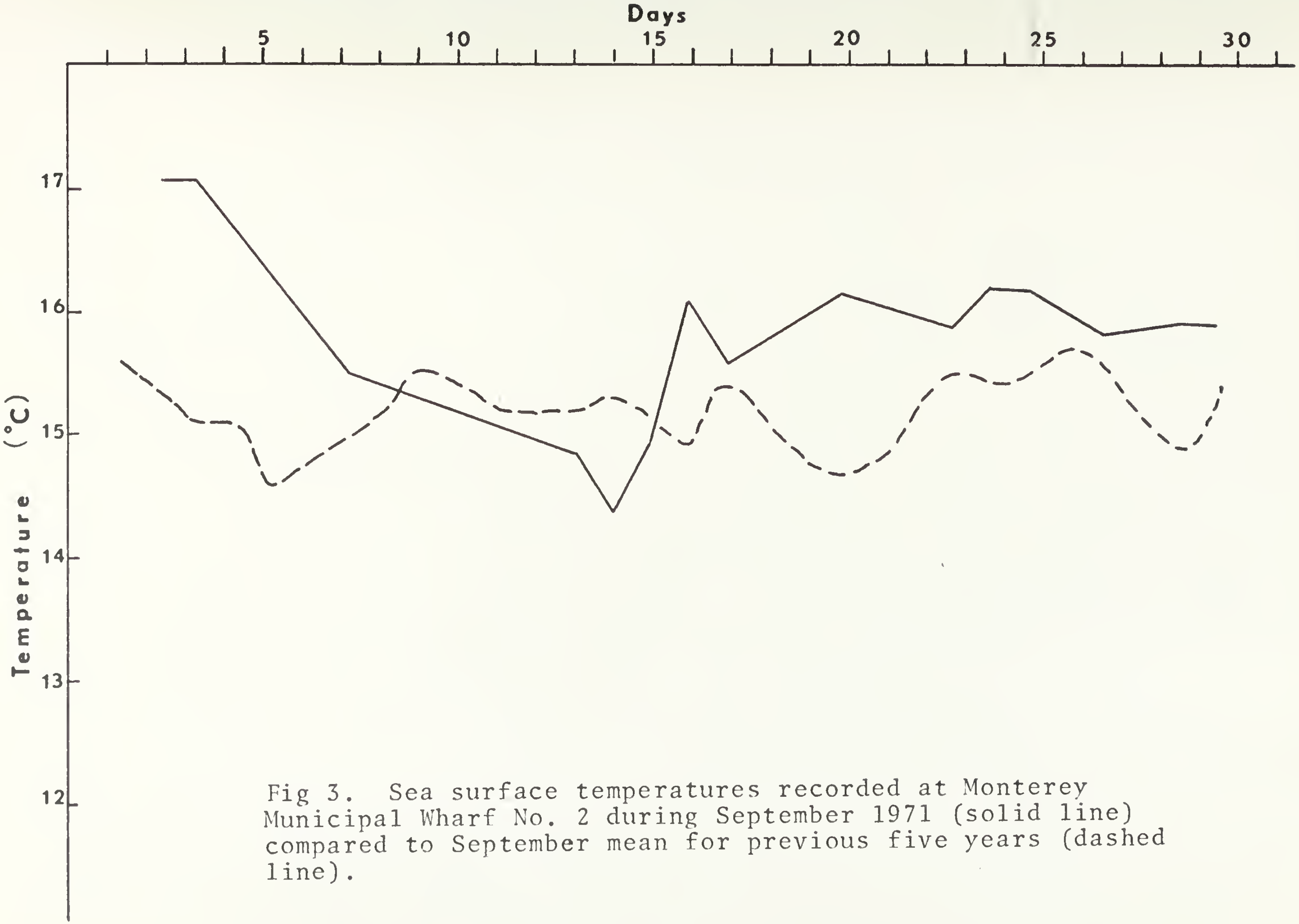

Fig 3. Sea surface temperatures recorded at Monterey Municipal Wharf No. 2 during September 1971 (solid line) compared to September mean for previous five years (dashed line).

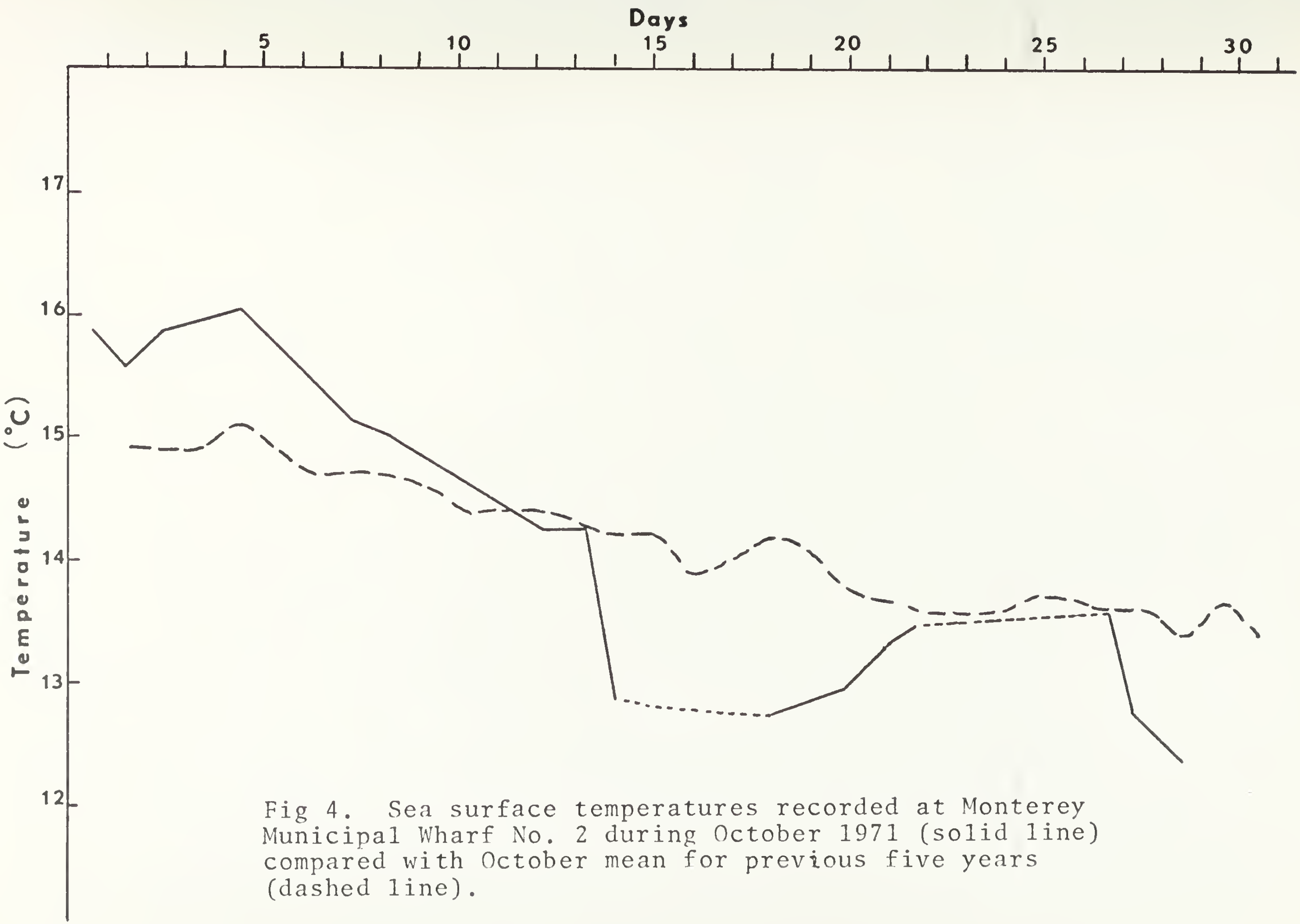

Fig 4. Sea surface temperatures recorded at Monterey Municipal Wharf No. 2 during October 1971 (solid line) compared with October mean for previous five years (dashed line).

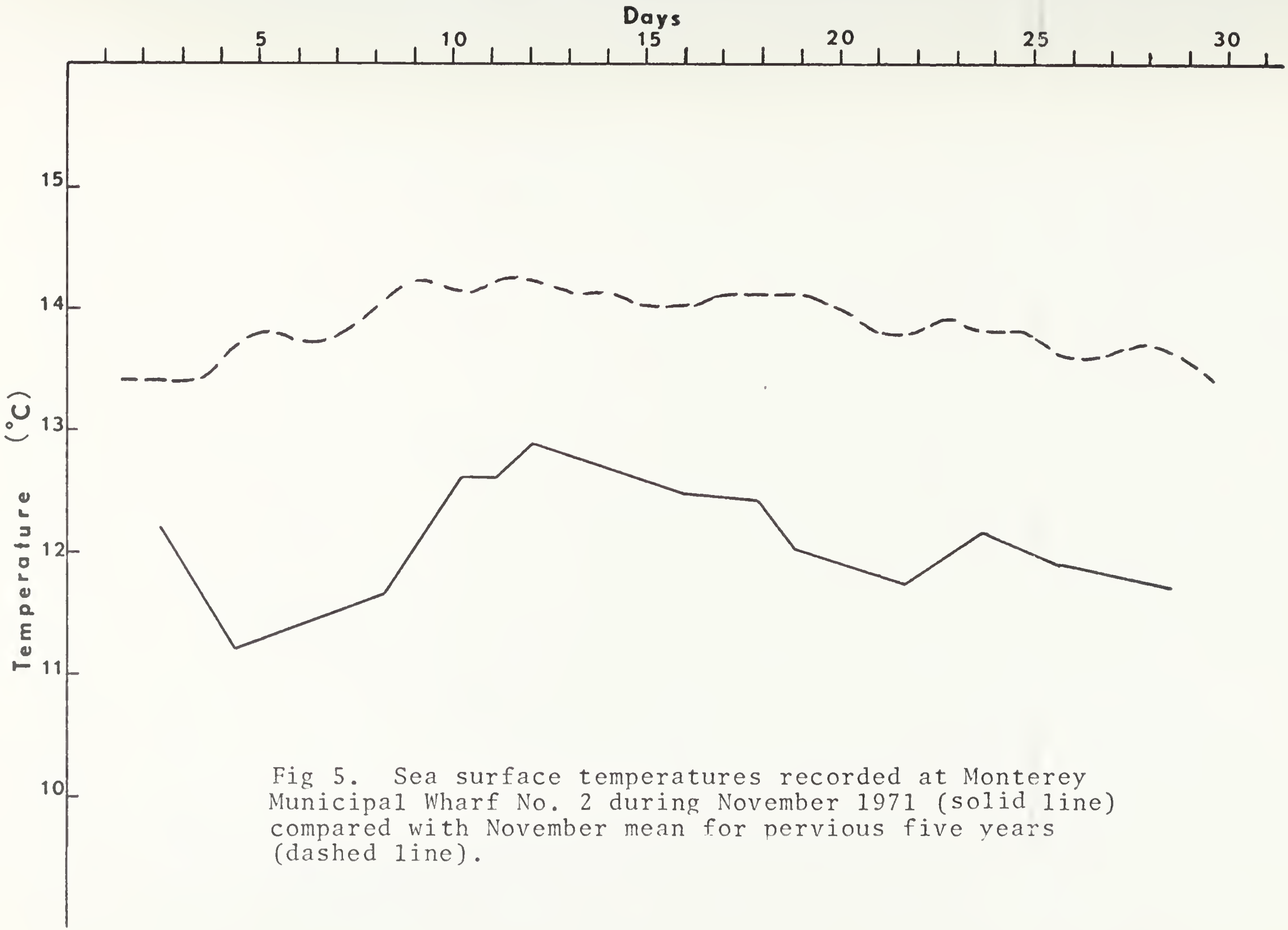

Fig 5. Sea surface temperatures recorded at Monterey Municipal Wharf No. 2 during November 1971 (solid line) compared with November mean for pervious five years (dashed line).

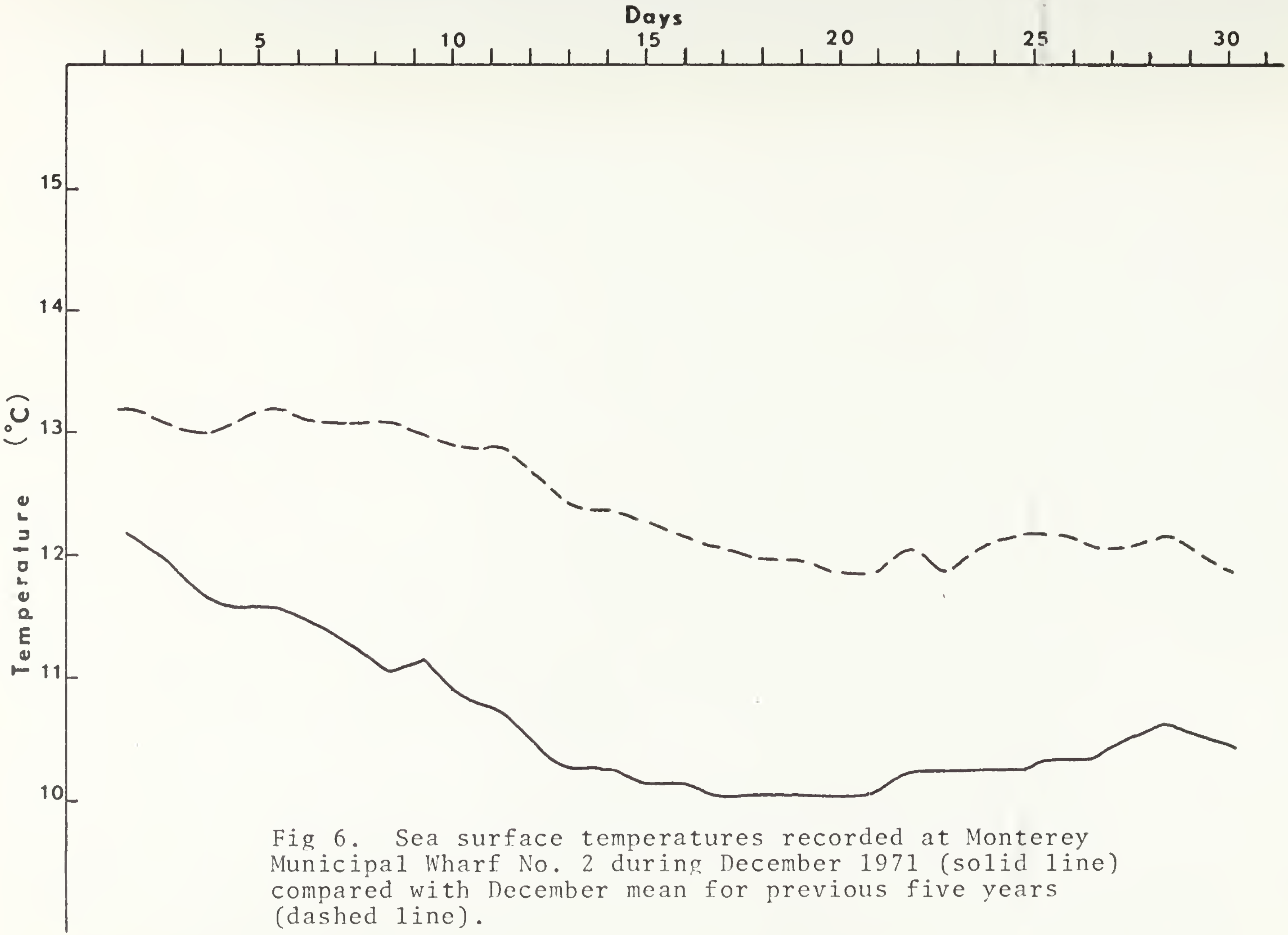

Fig 6. Sea surface temperatures recorded at Monterey Municipal Wharf No. 2 during December 1971 (solid line) compared with December mean for previous five years (dashed line).

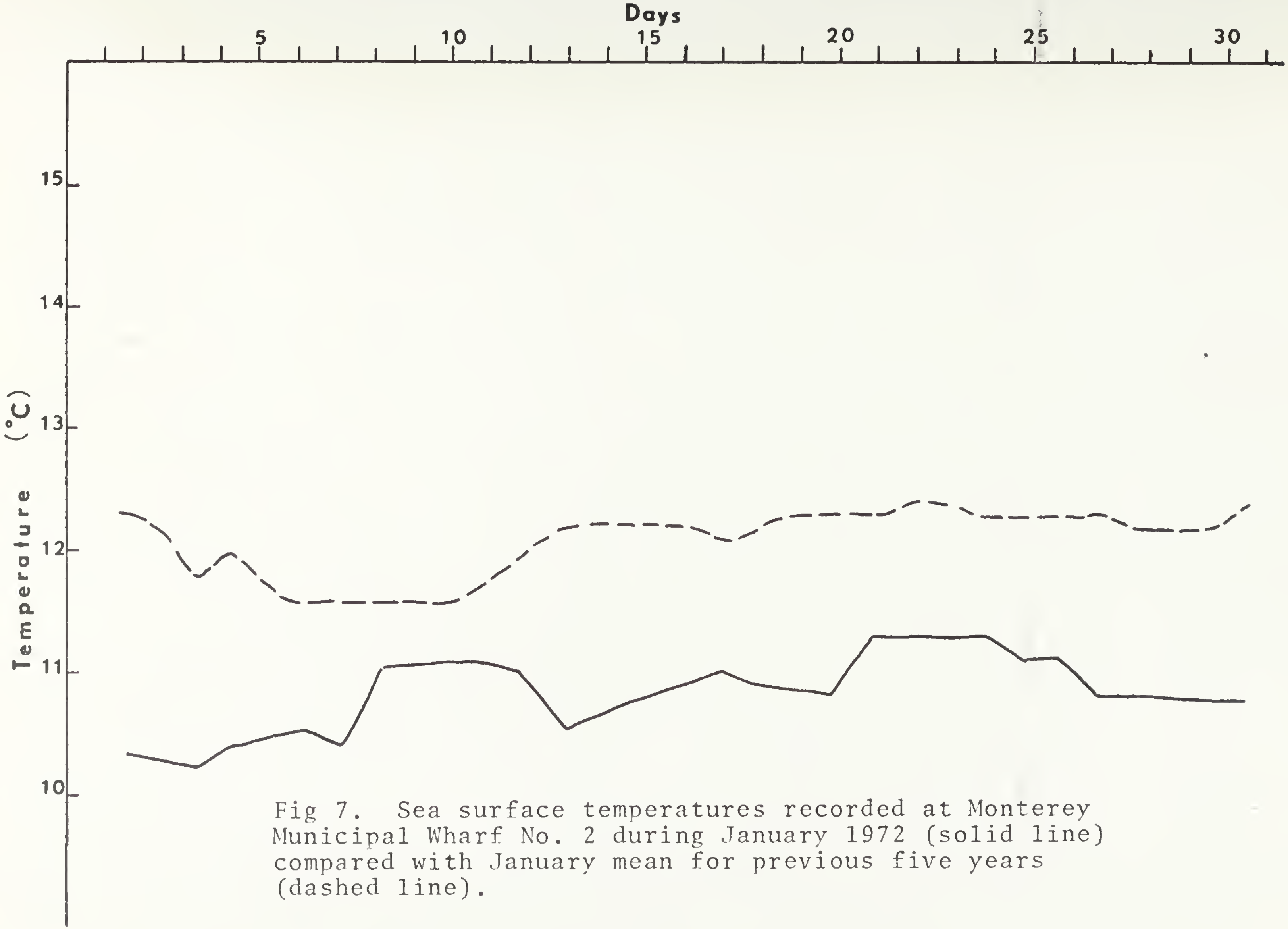

Fig 7. Sea surface temperatures recorded at Monterey Municipal Wharf No. 2 during January 1972 (solid line) compared with January mean for previous five years (dashed line).

C. FLUCTUATIONS IN THERMAL STRUCTURE

Both Skogsberg and Bolin noted the rapid fluctuations of thermal features in Monterey Bay. These fluctuations are indicated in the time series charts for each station (Figs. 9 through 17).

In order to further evaluate the vertical migrations of the isotherms in the upper 500 meters a cruise was planned such that Stations 2, 4, and 5 (see Fig. 1) would each be observed four times at three-hour intervals. The observations were begun at the time of high tide as computed for Monterey and concluded at the next high tide. STD and XBT casts were made on the first round of the stations, and then XBT drops only for the next three observations of each station. The results of the bathythermograph drops for Stations 2, 4, and 5 are plotted on Fig. 8. The maximum isotherm migration at Station 2 was between 0925 hours and 1225 hours when the 7°C isotherm lowered 50 meters. At Station 4 the 8°C isotherm dropped 64 meters between 0415 hours and 0715 hours. Maximum isothermal motion over a three-hour period was 90 meters from the 7°C isotherm at Station 5 in the interval 0505 hours to 0805 hours. There was little apparent correlation between the surface tides and the changes in isotherm depth observed in this series, but the requirement of three hours of ship steaming time for each circuit of the stations made it impossible to observe variations on a smaller time scale. It would have been useful to extend the duration of

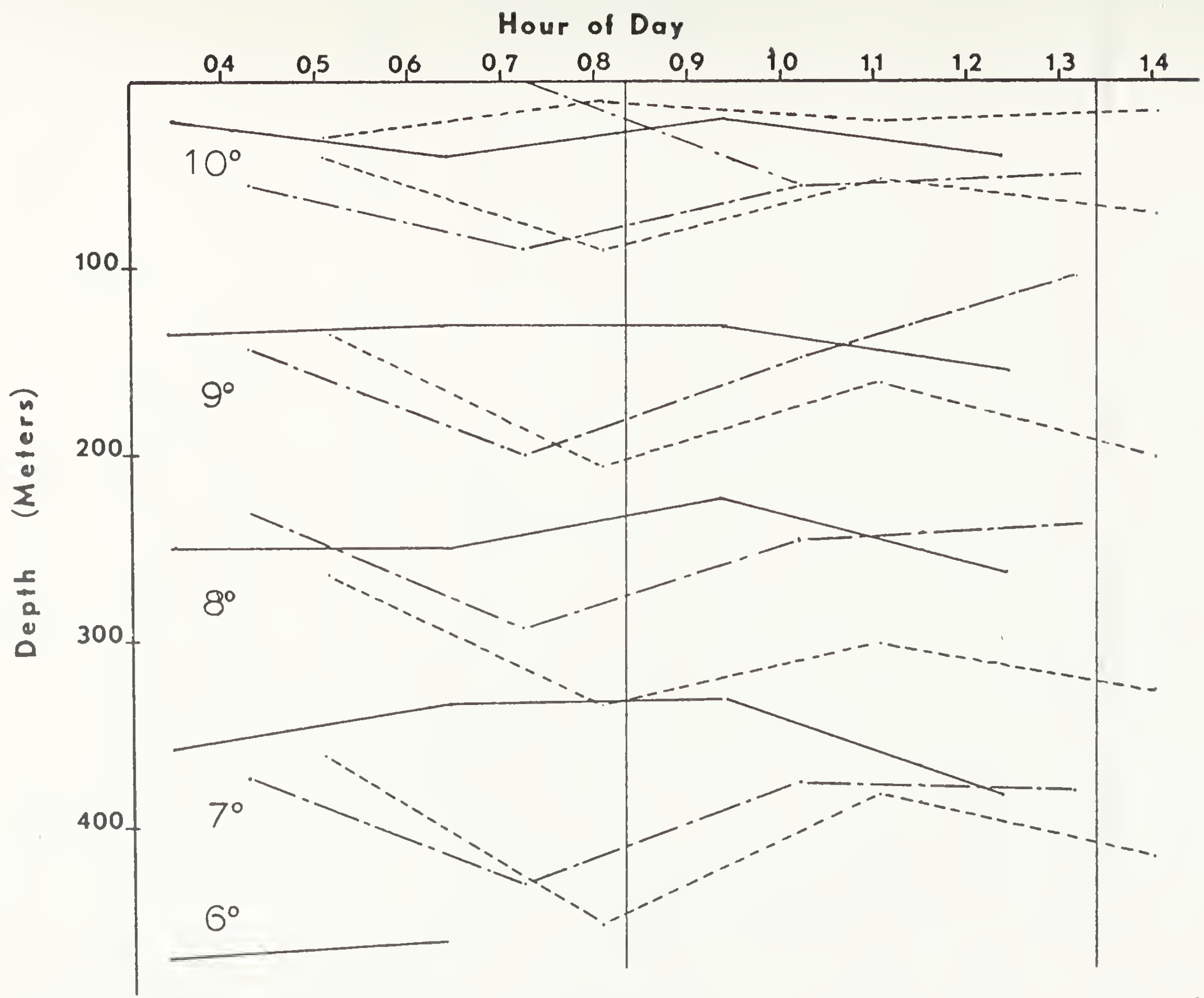

Fig 8. Fluctuations in isotherms at stations 2 (solid line), 4 (broken line) and 5 (dashed line) observed at three-hour intervals during one tidal cycle on 18 December 1971. High tides at Monterey were at 0302 and 1326; low tide was at 0820.

this cruise an additional 12 hours and to make hourly observations at the three stations simultaneously. This was not possible.

Figures 9 through 17 show isotherm depths as observed at Stations 1 through 9, respectively, through the time interval 21 September 1971 to 28 January 1972. Observation points are essentially one week apart with the exception of 21-23 September during which time the series of stations was completed once on each of the three days. Over these days, for fluctuations observed on the order of a day apart, Stations 2, 3, and 4 showed 100 meter, 115 meter, and 105 meter vertical movement in the 10°C, 9°C, and 10°C isotherms, respectively. It is observed that the 9°C isotherm at Station 2 was the most sensitive and showed two weekly changes on the order of 250 meters in the first half of January. At Station 8 the 9°C isotherm was again the most active showing a drop of 165 meters in the third week of December.

D. SEA SURFACE TEMPERATURES AND THERMAL GRADIENTS TO 50 METERS AND 100 METERS

Figures 18 through 22 illustrate the fluctuations in sea surface temperature and thermal gradients between the surface and 50 and 100 meters as averaged among all nine bay stations at two-week intervals. The lower two solid line curves in each figure [$(T_o - T_{50m})$ and $(T_o - T_{100m})$] are actually the nine-station averaged differences in temperature between the surface and 50 meters (upper curve), and the

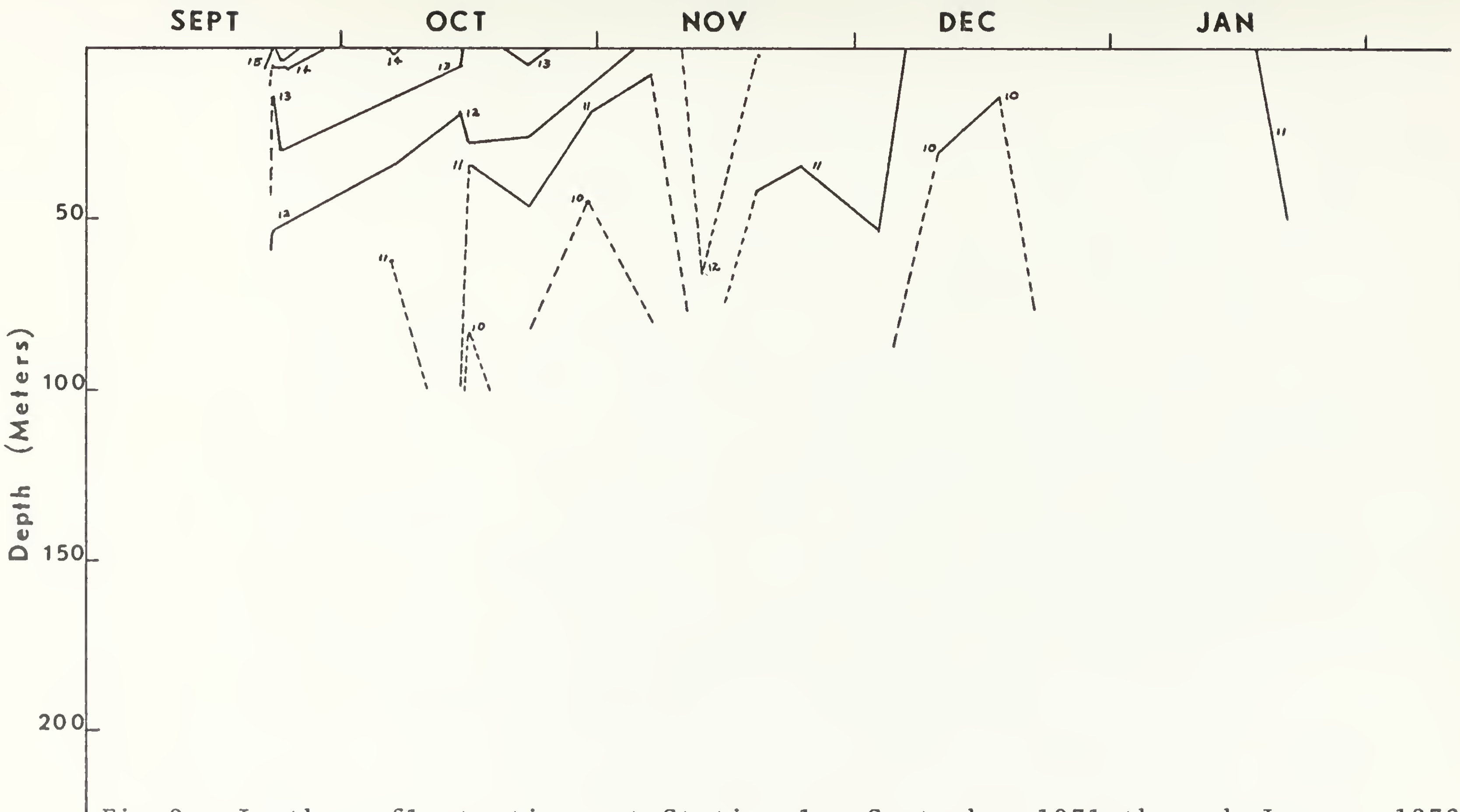

Fig 9. Isotherm fluctuations at Station 1. September 1971 through January 1972.

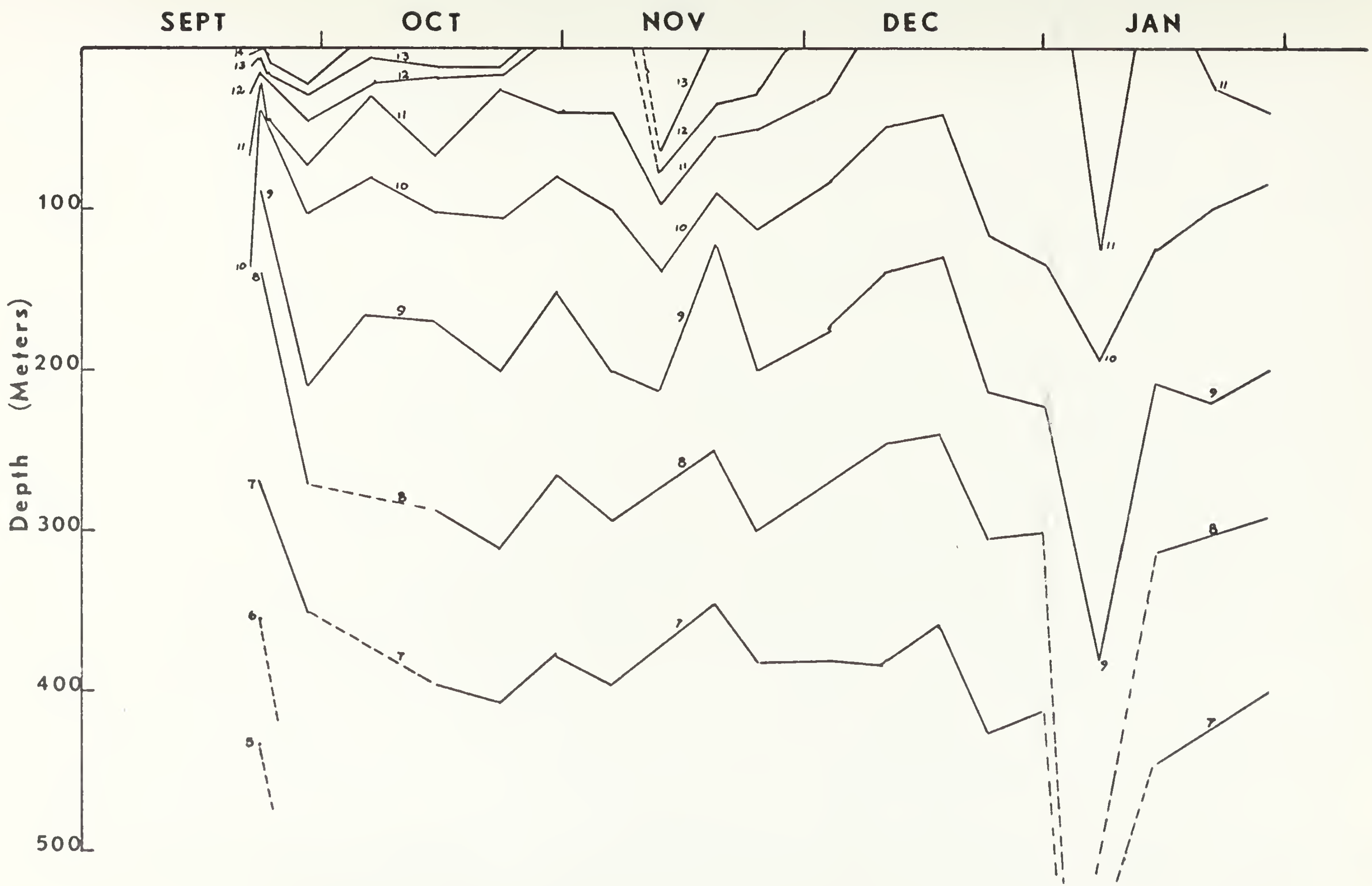

Fig 10. Isotherm fluctuations at Station 2. September 1971 through January 1972.

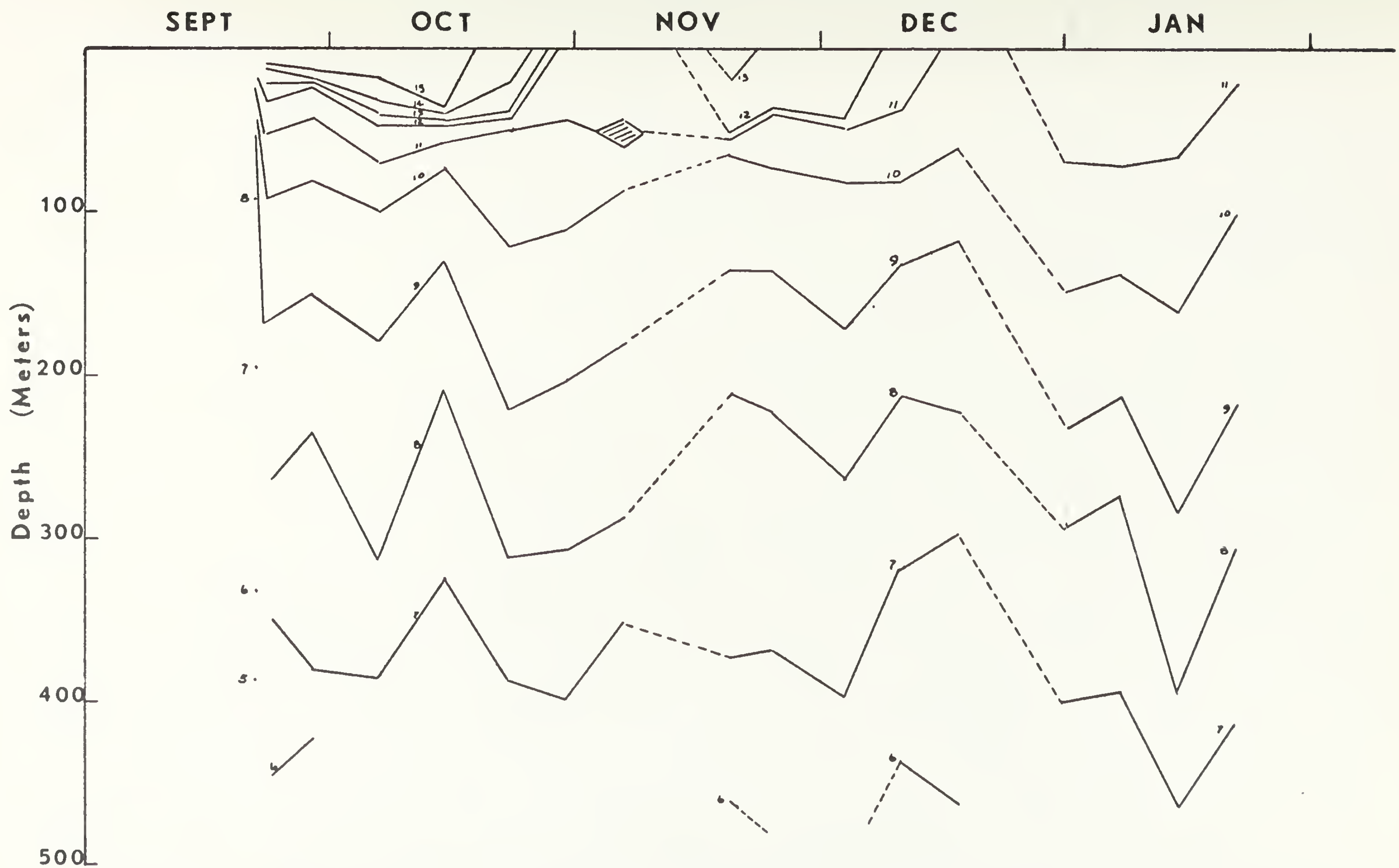

Fig 11. Isotherm fluctuations at Station 3. September 1971 through January 1972.

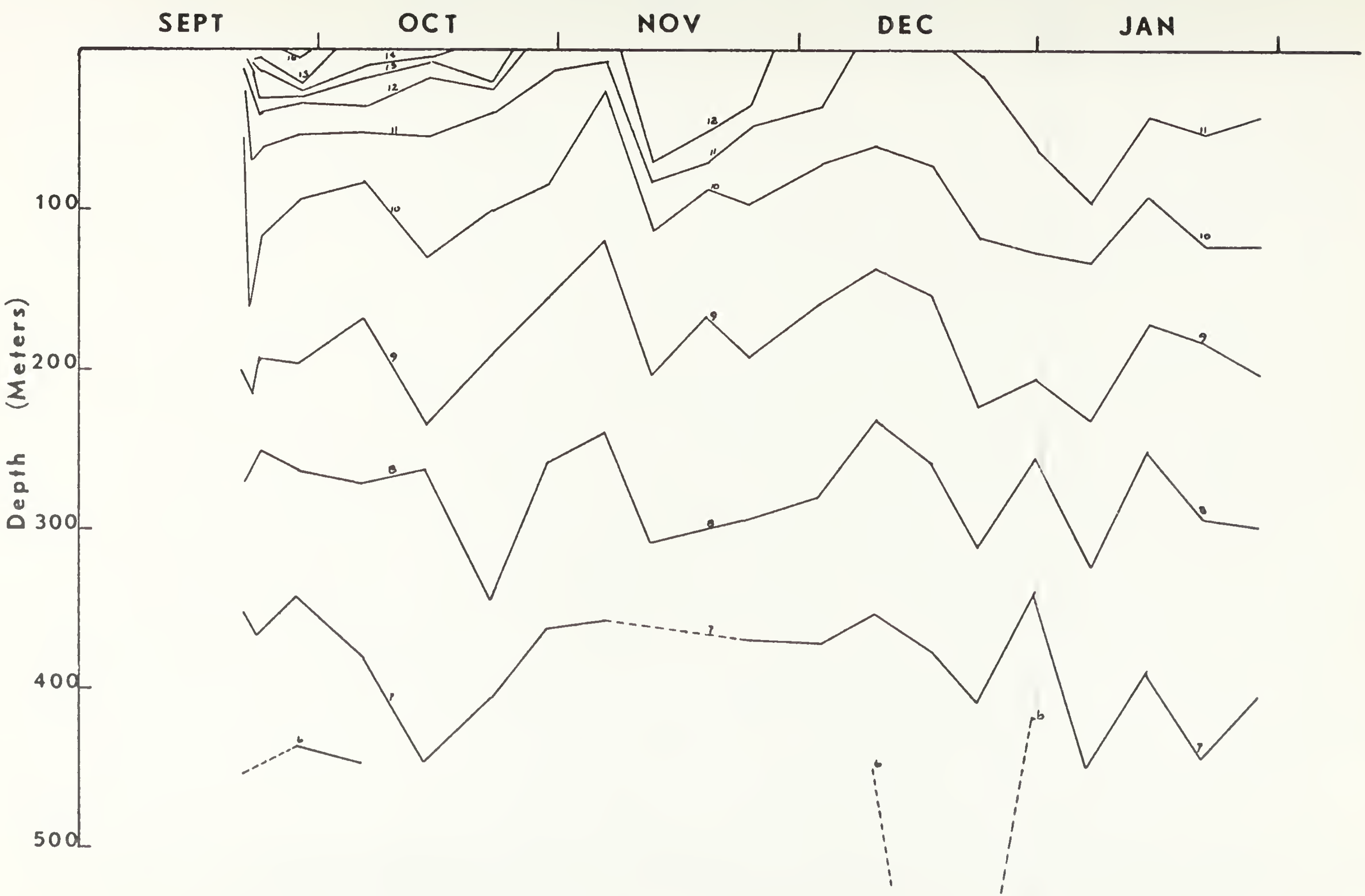

Fig 12. Isotherm fluctuations at Station 4. September 1971 through January 1972.

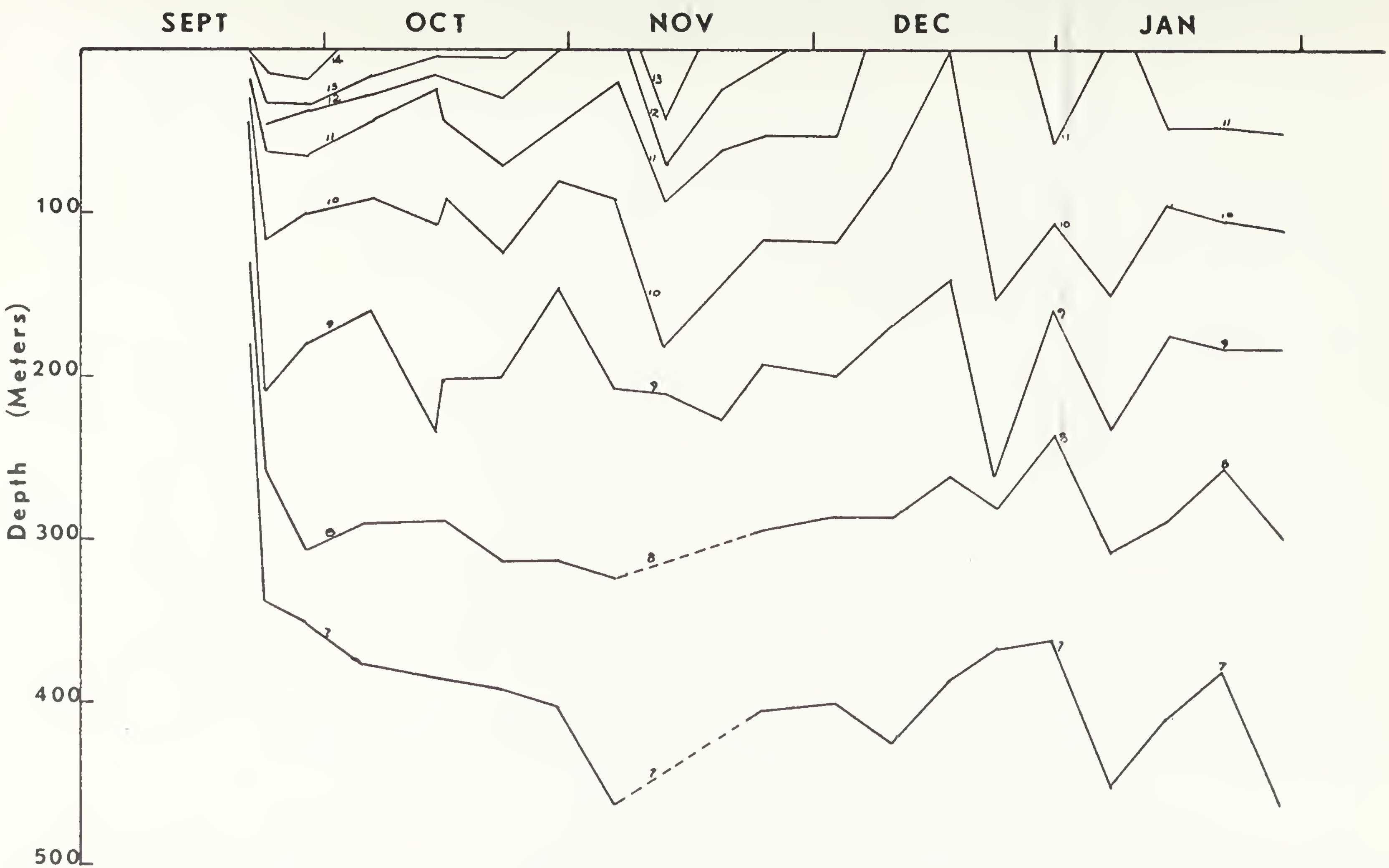

Fig 13. Isotherm fluctuations at Station 5. September 1971 through January 1972.

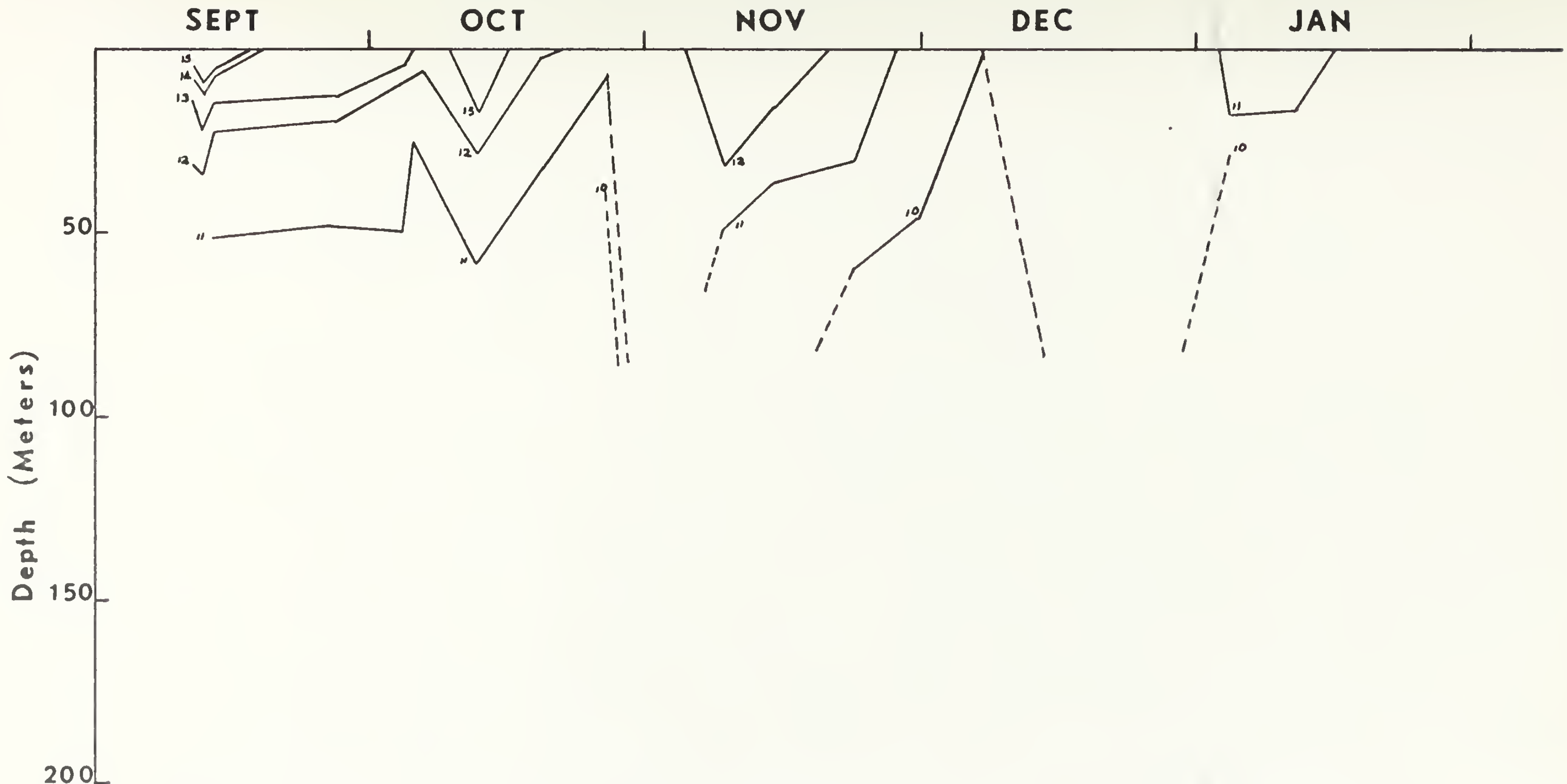

Fig 14. Isotherm fluctuations at Station 6. September 1971 through January 1972.

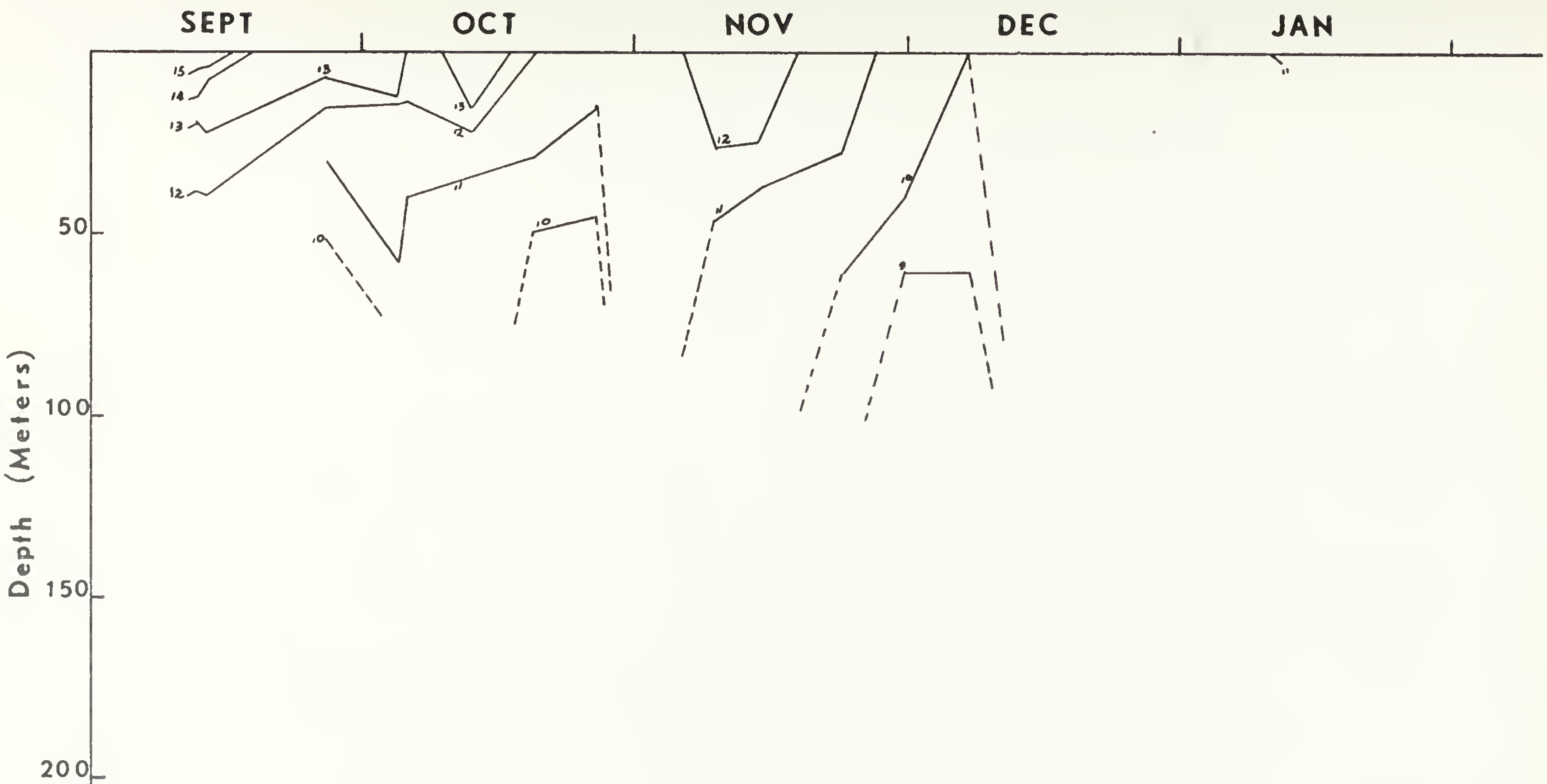

Fig 15. Isotherm fluctuations at Station 7. September 1971 through January 1972.

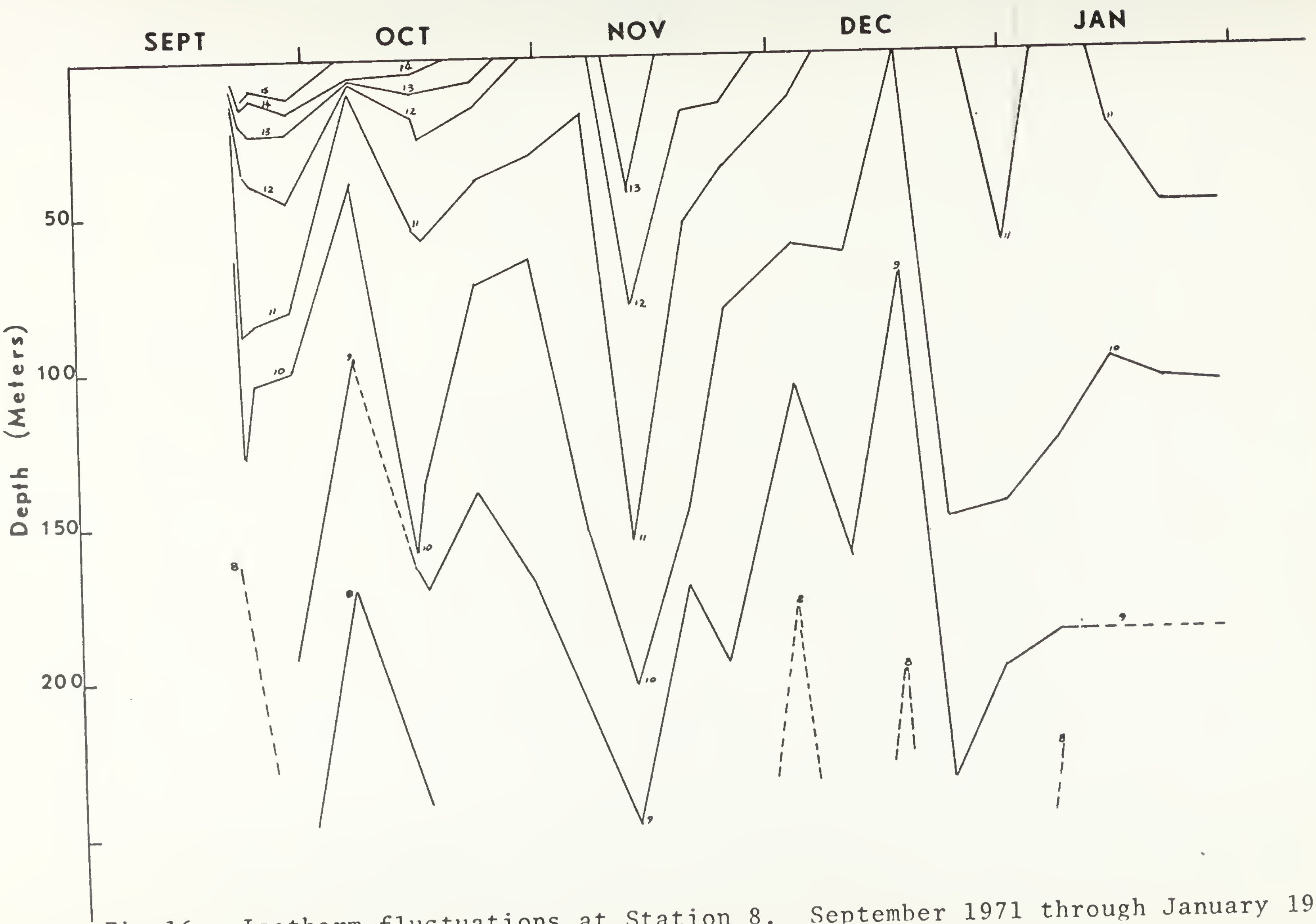

Fig 16. Isotherm fluctuations at Station 8. September 1971 through January 1972.

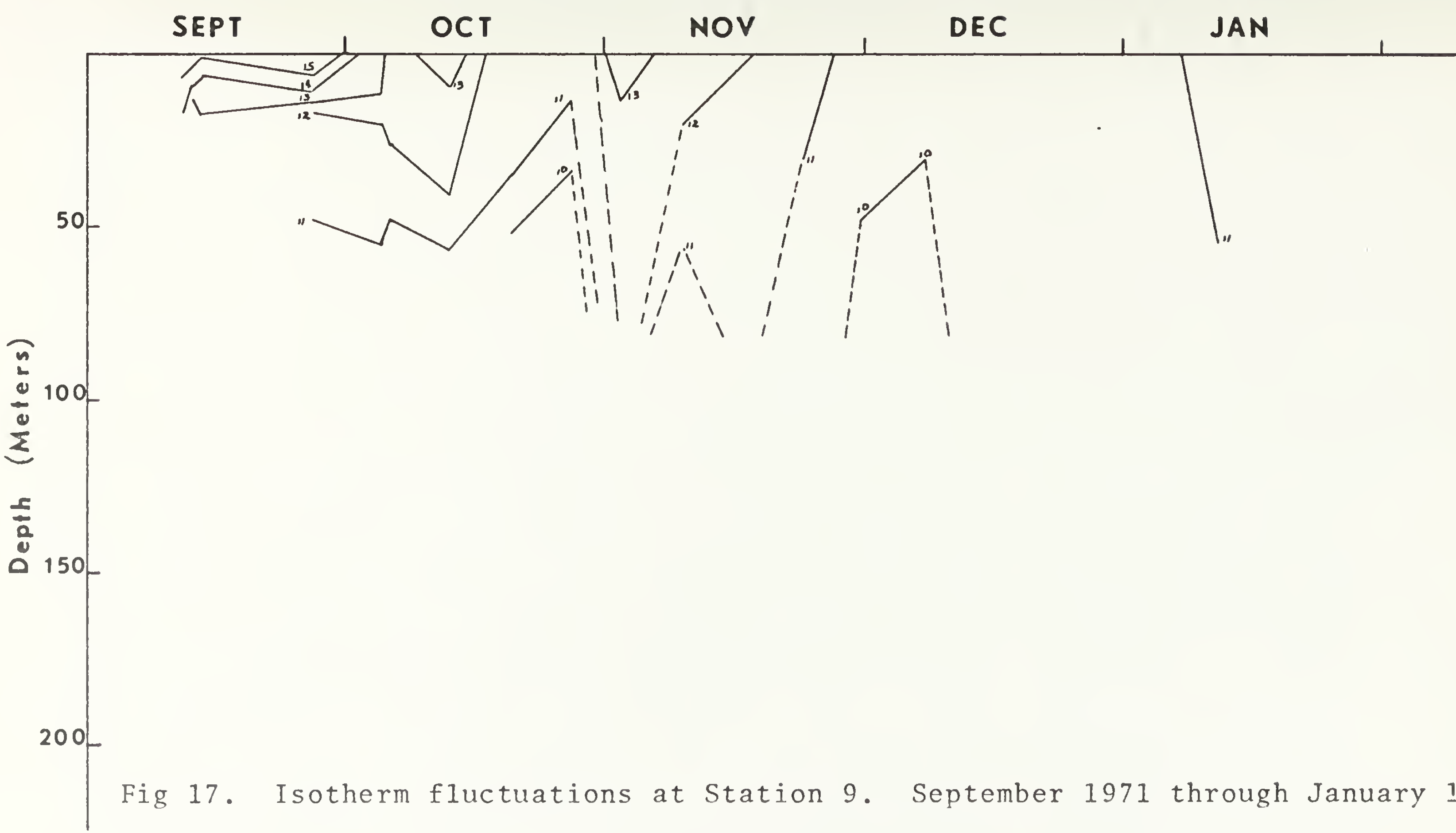

Fig 17. Isotherm fluctuations at Station 9. September 1971 through January 1972.

surface and 100 meters (lower curve). Figures 18 and 21 do not have temperature differences to 100 meters shown since the water depth at Stations 1 and 6 is less than 100 meters. Superimposed upon these bay average curves are the values for Stations 1, 3, 5, 6, and 8 (dashed lines) in the respective figures. The information for these stations was dashed to show which stations most nearly approximated the averaged behavior of the full set of observed stations over the period of this study.

These figures were of particular interest considering Skogsberg's description of the three cyclic regimes observed in Monterey Bay. During the end of September and October the highest sea surface temperatures in 1971 (approximately 12.7°C) and the strongest gradients to 50 and 100 meters occurred. The sea surface temperature decreased and the gradient to 100 meters weakened from September 1971 through December 1972 except during the last half of November. This interval of increased gradient and increased surface temperature suggest a final recurrence of the Oceanic Period dividing the Upwelling and Davidson Current regimes.

A weak thermal gradient and the presence of relatively warm waters from the surface to 50-100 meters are characteristic of the Davidson Current Period. From early December through January the temperature difference to 100 meters was less than 10°C and Stations 3 and 5 even exhibited thermal inversions in the upper 50 meters.

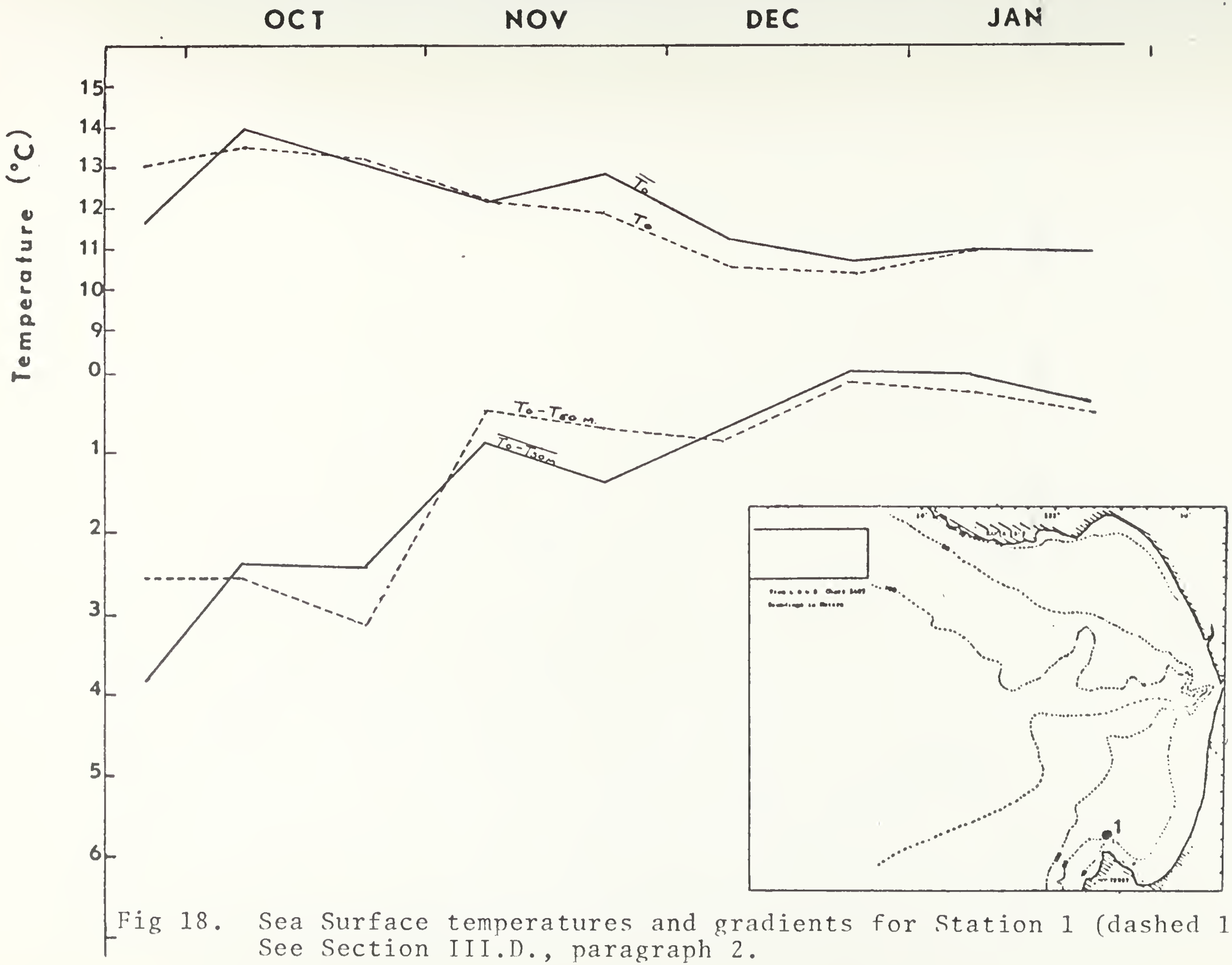

Fig 18. Sea Surface temperatures and gradients for Station 1 (dashed lines). See Section III.D., paragraph 2.

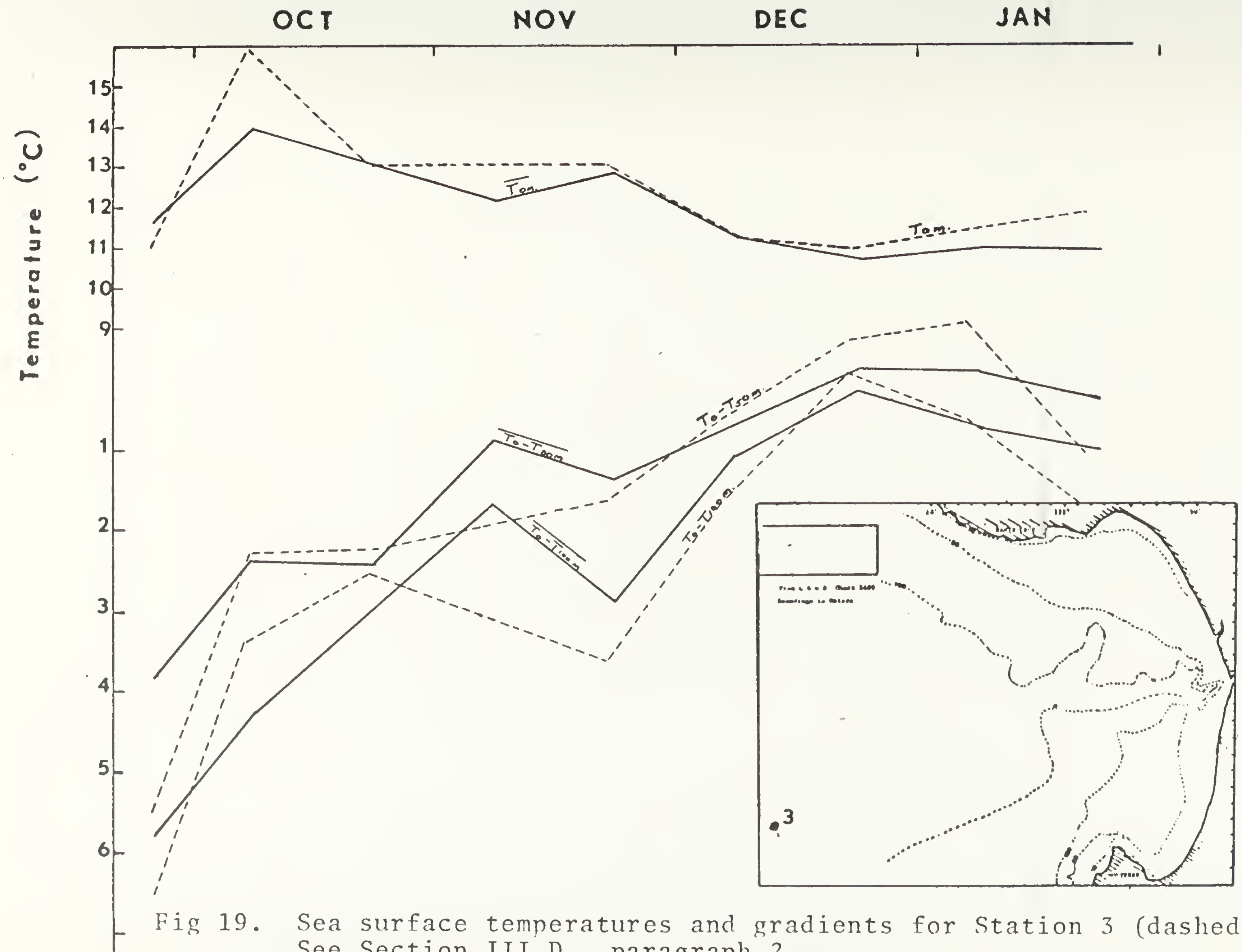

Fig 19. Sea surface temperatures and gradients for Station 3 (dashed lines). See Section III.D., paragraph 2.

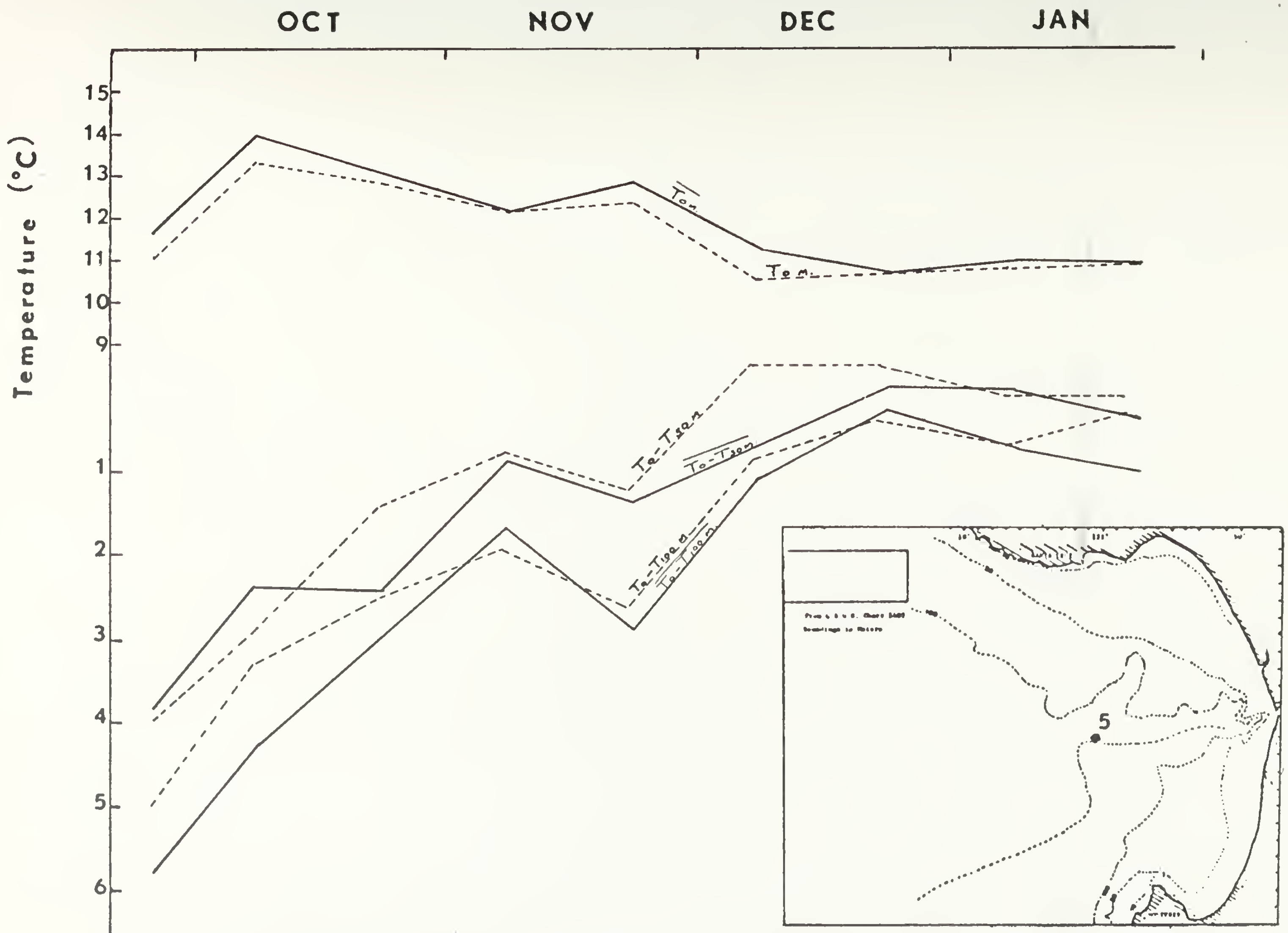

Fig 20. Sea surface temperatures and gradients for Station 5 (dashed lines). See Section III.D., paragraph 2.

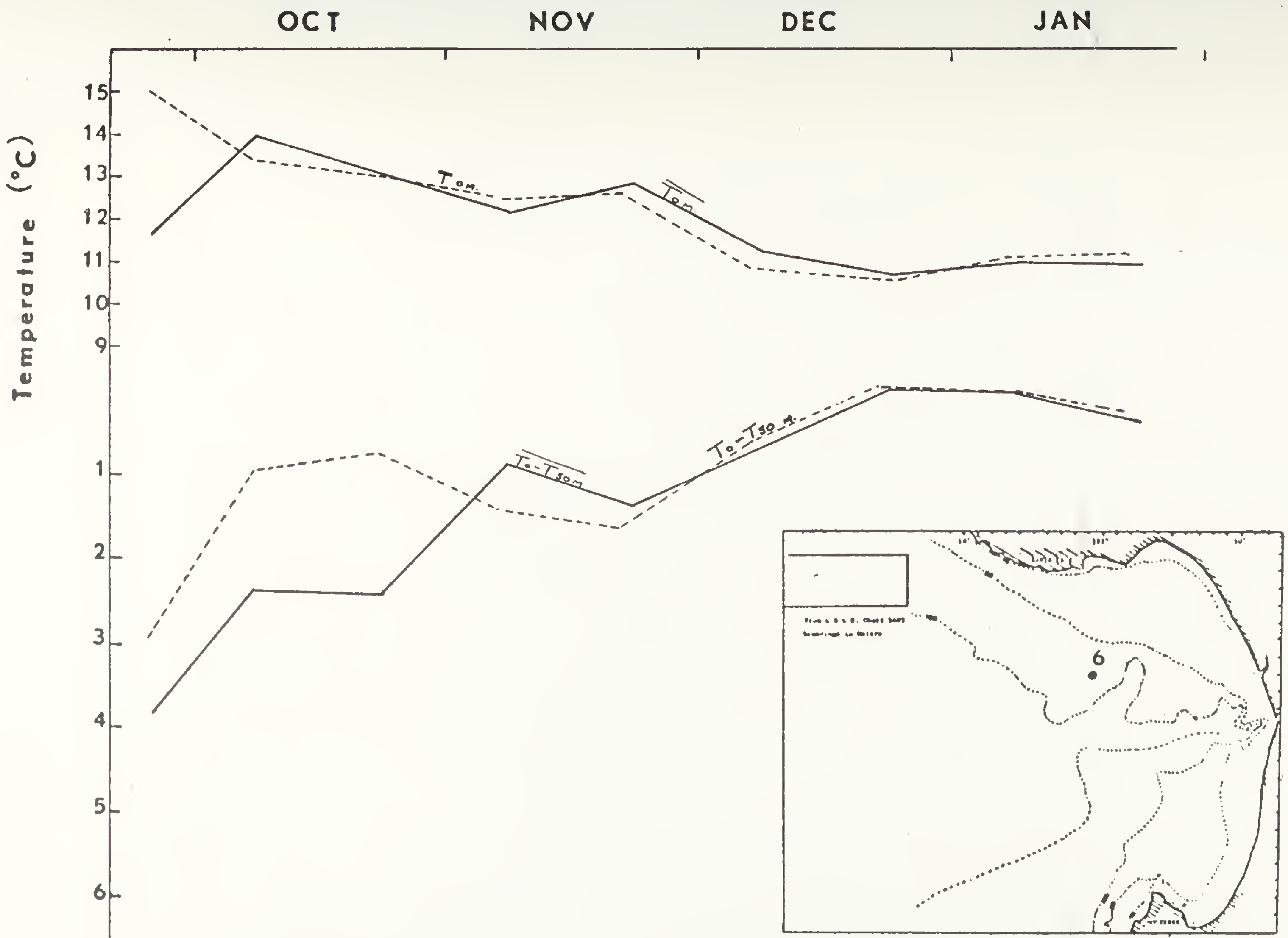

Fig 21. Sea surface temperatures and gradients for Station 6 (dashed lines). See Section III.D., paragraph 2.

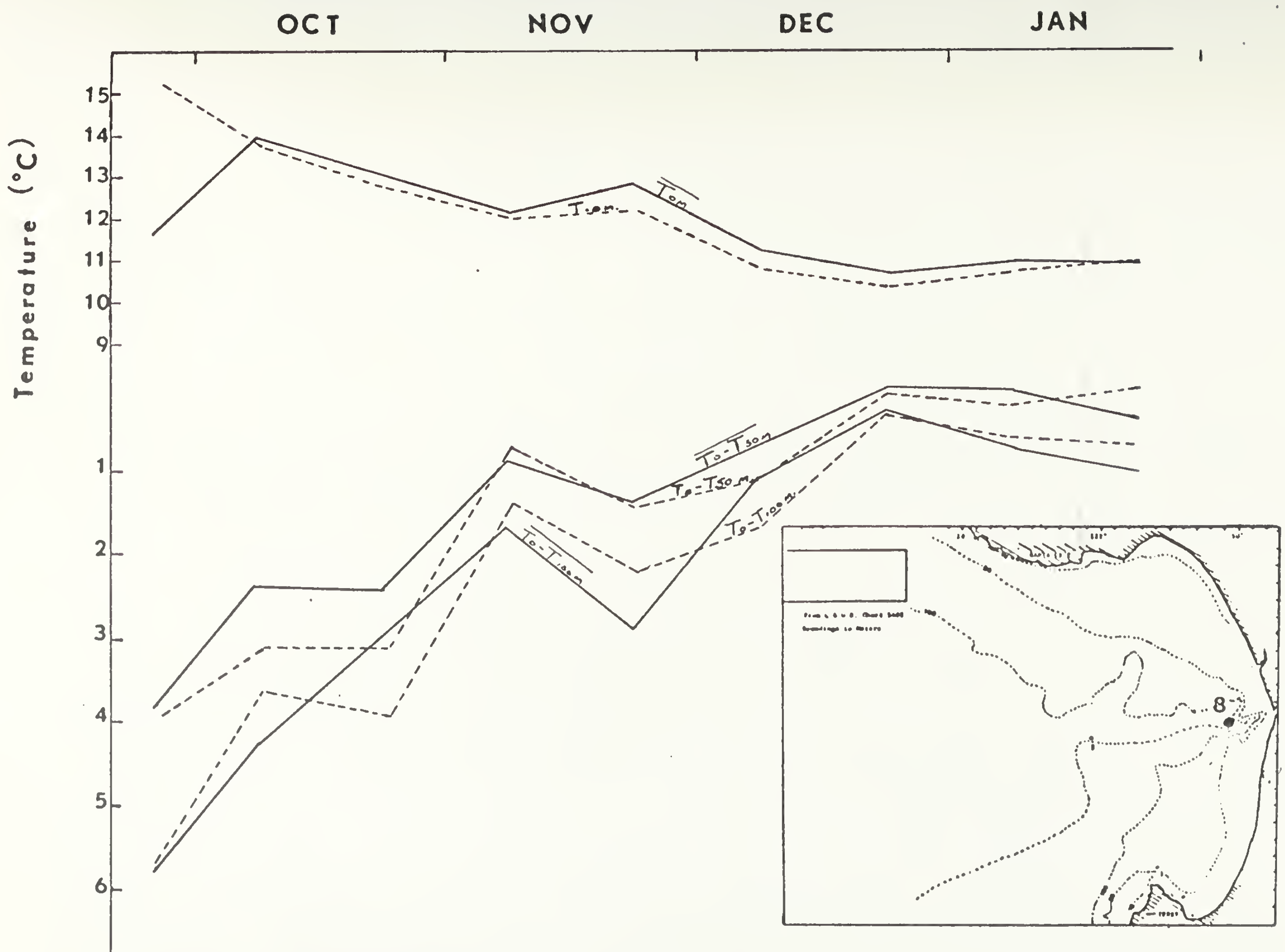

Fig 22. Sea surface temperatures and gradients for Station 8 (dashed lines). See Section III.D., paragraph 2.

E. TWO-STATION COMPARISON GRAPHS

Graphs of the types shown in Figs. 23, 24, and 25 were used by Anderson to illustrate the comparative changes with time in sea-surface temperature for a pair of stations. Each point on the graph shows the temperature at each station. The horizontal temperature gradient can be found if the distance between stations is known. Anderson's graphs indicate the cyclic progression of the seasons in Monterey Bay, and Figs. 23 and 24 show part of this annual cycle as observed during the present investigation. Anderson used the 40-year average data compiled by Lammers and his curves are plotted here for comparison with the new data. The heavy solid lines connect monthly mean values observed during this study, and the heavy dashed lines show the long term averages for September through January. The fine solid lines connect individual data points for September 1971 through January 1972. Figure 23 compares sea-surface temperature conditions at a mid-canyon station (5) and a southern shallows station (1). Station 5 is north of Station 1, and from the graph it can be seen which station changed temperature more rapidly and whether or not there was a directional tendency. It is obvious to the reader that motion along a positive 45-degree line implies an equal change in temperature at the two stations. A more vertical line segment indicates that the station represented along the ordinate changed more rapidly than the other station.

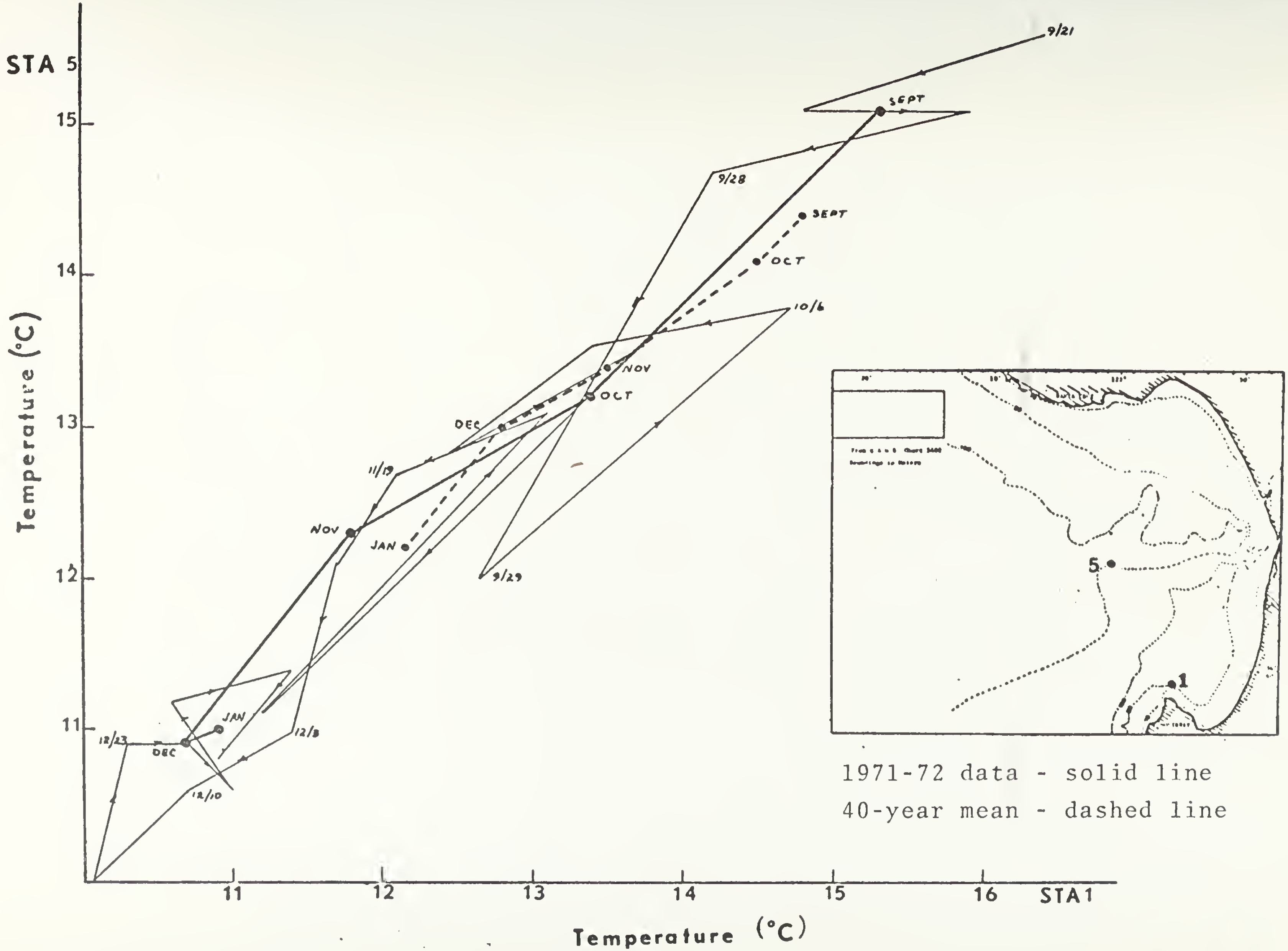

Fig. 23. Seasonal progression of sea surface temperatures at Stations ~~4~~ 1 and ~~8~~ 5.

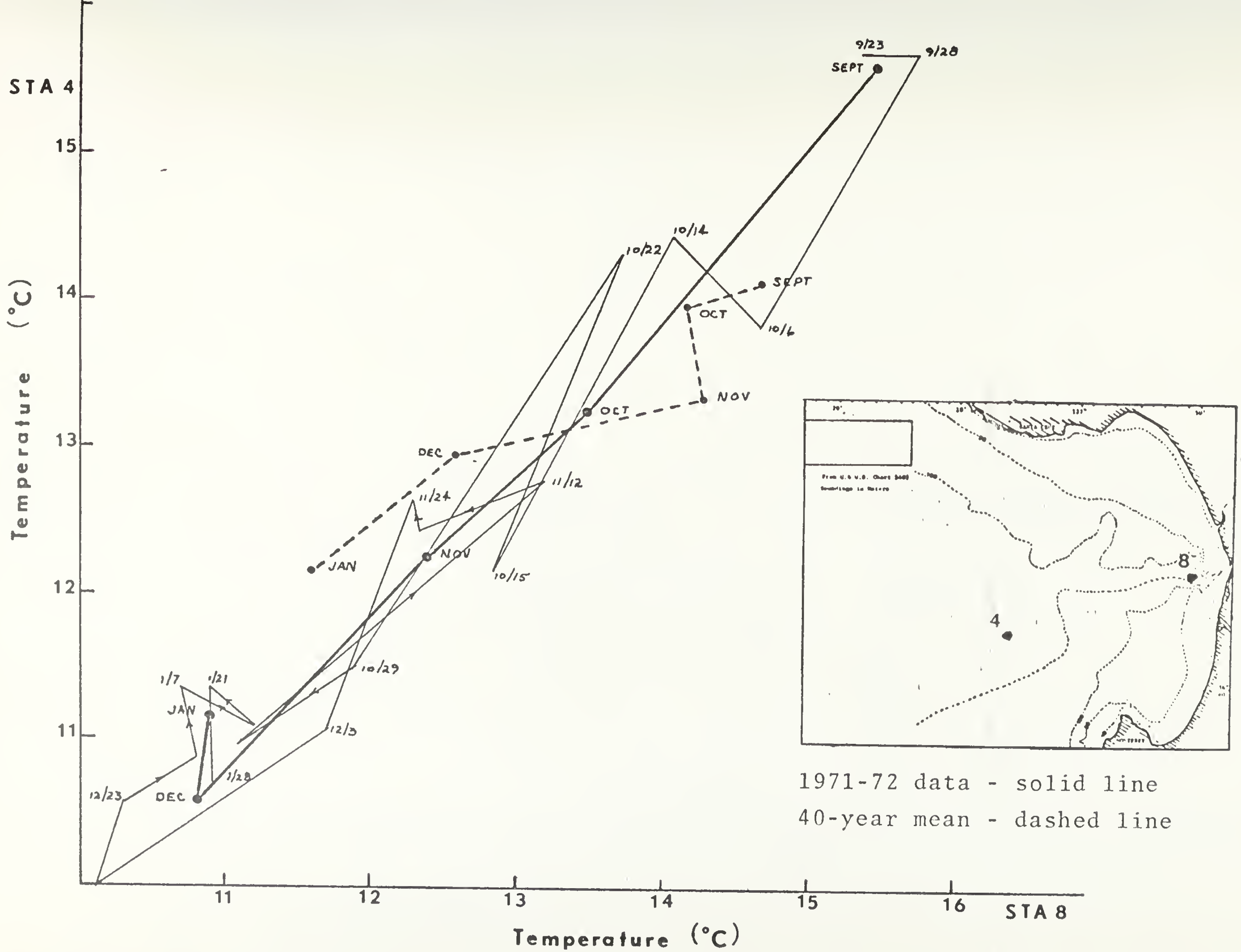

Fig. 24. Seasonal progression of sea surface temperatures at Stations 4 and 8.

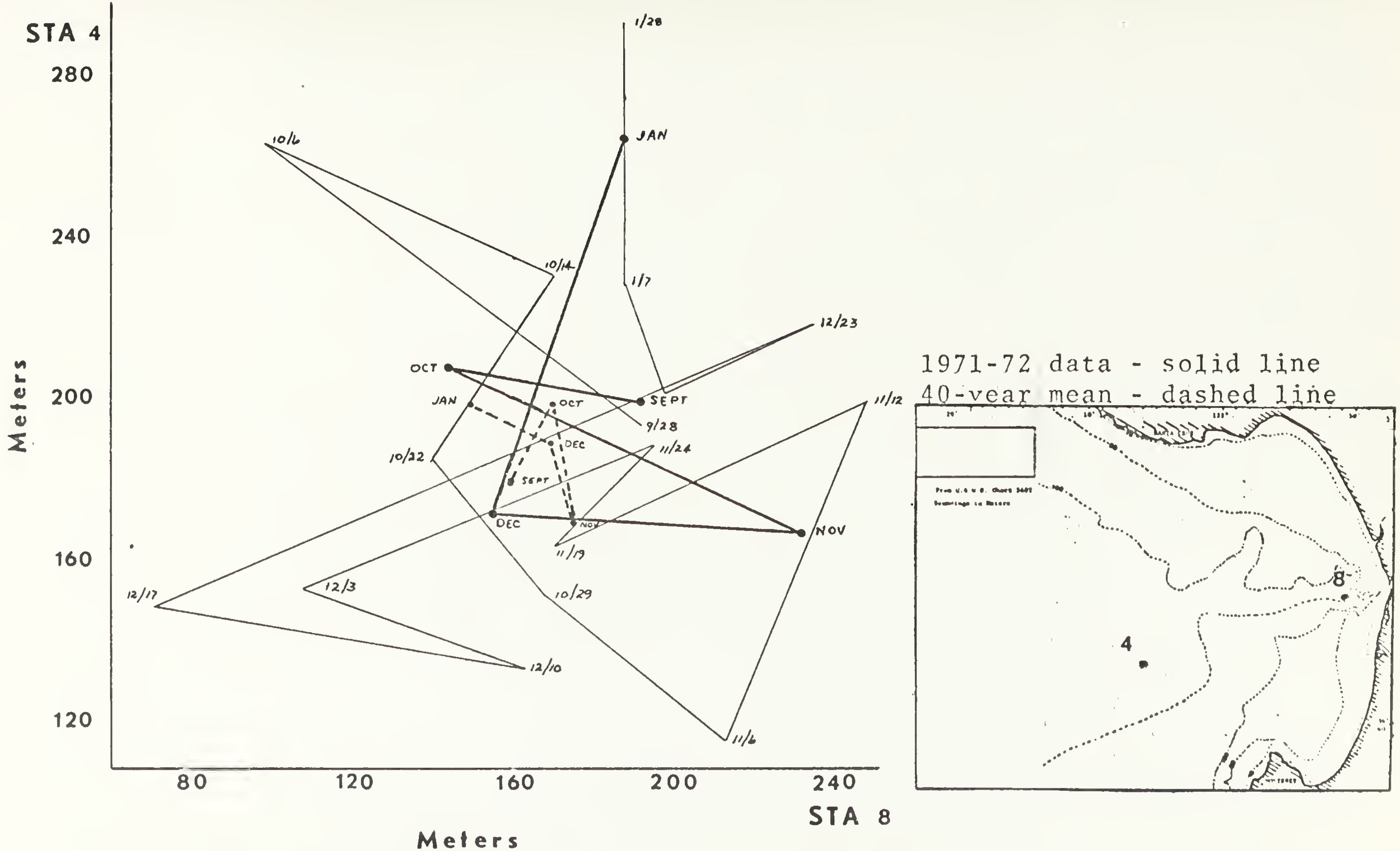

Fig 25. Seasonal progression of the depth of the 9°C isotherm for Stations 4 and 8.

The cruise-to-cruise data points show the very rapid changes in temperature that were characteristic of the bay during this study. Comparison of the two heavy lines shows how very different the 1971-1972 period was from the long-term average. The mean sea-surface temperature at Station 5 was 0.7°C warmer than the 40-year mean for September, but the October 1971 mean was not only cooler than the long-term October mean, but was also cooler than the long-term November mean. These extremes reflect the anomalously rapid cooling of the bay in 1971, and the slope of this line segment shows that the two stations, in the mean, cooled at the same rate. The November mean was just slightly (0.1°C) warmer than the long-term January mean, and it is seen that Station 1, a shallow station, cooled more than the deeper canyon station, Station 5. The mean temperature for the month of December was 2.1°C lower than the 40-year mean for December. The proximity of the January 1972 mean to that for December 1971 indicates that the bay surface temperature was essentially static during that period.

Figure 24 shows the same relationship as Fig. 23, but for Stations 4 and 8, an east-west pair. Both of these stations are in the canyon, but 4 is in 1,500 meters of water while 8, at the head of the canyon, is in roughly 200 meters of water. This figure shows an even greater, more uniform drop in sea-surface temperature than the preceding graph. The western, deeper station of this pair cooled slightly faster than the other from September through

December, and warmed 0.6°C in January, whereas Station 8 warmed by only 0.1°C. This warming in January was contrary to what one would expect from all examination of the long-time mean since Stations 4 and 8 should apparently have cooled approximately 0.8°C. The January warming may have indicated a trend toward more "normal" temperatures in February.

Figure 25, similar to the preceding two graphs, shows the change in the depth of the 9°C isotherm at Stations 4 and 8. Again, in this graph, the slope of the line segments relative to the 45-degree line is an important indication of the relative rate of change of the isotherm depth for each section. Immediately apparent are the wide fluctuations in the depth of this isotherm during this period vice the relatively static behavior indicated by the long-term averages. Station 8 was the more active of the two through December showing a decrease in isotherm depth (cooling) in both October and December, and an increase in isotherm depth (warming) in November. These trends are also noticeable in Figures 18 through 22 which show the temperature gradients to 50 and 100 meters. The mean 9°C isotherm depth in January increased 93 meters over December at Station 4 indicating a definite warming at about 200 meters. This same isotherm increased in depth over 30 meters at Station 8 in January. The warming at about 200 meters at these two stations may have resulted from the advection of warm water into the Monterey Canyon from the Davidson Current.

Further comparison of data collected during this study with the long-term means derived by Lammers is shown in Figs. 26 through 32. Lammers used the block average values to plot the sea surface temperatures and 10°C and 9°C isotherms for three characteristic areas of Monterey Bay. Blocks 1, 3, and 19 of Lammers' coincided with Stations 1, 5, and 8 of this study. Data points observed from September 1971 through January 1972 are plotted on the long-term averages for comparison.

The lower than "normal" sea surface temperatures for these three stations during this research are obvious. The fluctuations in sea-surface temperature for the three stations are comparable but a definite difference in the degree of change in isotherm depth is observed at Stations 5 and 8.

Clearly the 9°C isotherm is more sensitive to change than the 10°C isotherm, and changes in isotherm depth at Station 8 are greater than the changes at Station 5. The observed sensitivity of the 9°C isotherm verified the opinion of Skogsberg that the fluctuations of the isotherm are useful in defining the three cyclical regimes in Monterey Bay.

The more extreme changes in isotherm depth observed at Station 8 have been commented upon earlier in this paper, and are attributed to the location of this station with respect to the topography of the Monterey Canyon.

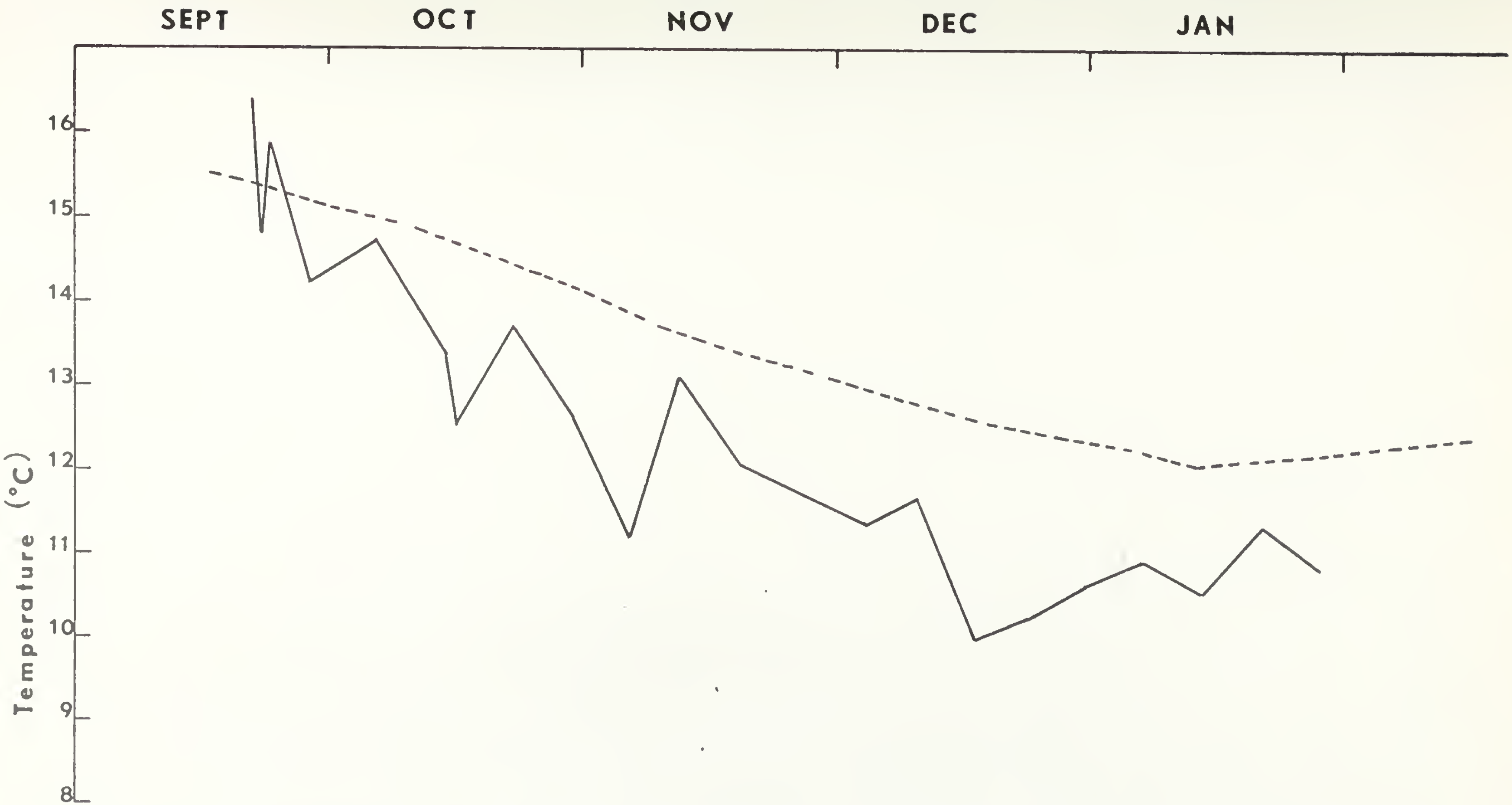

Fig 26. Changes in sea surface temperature at Station 1 (solid line) compared with long-term average computed by Lammers (dashed line).

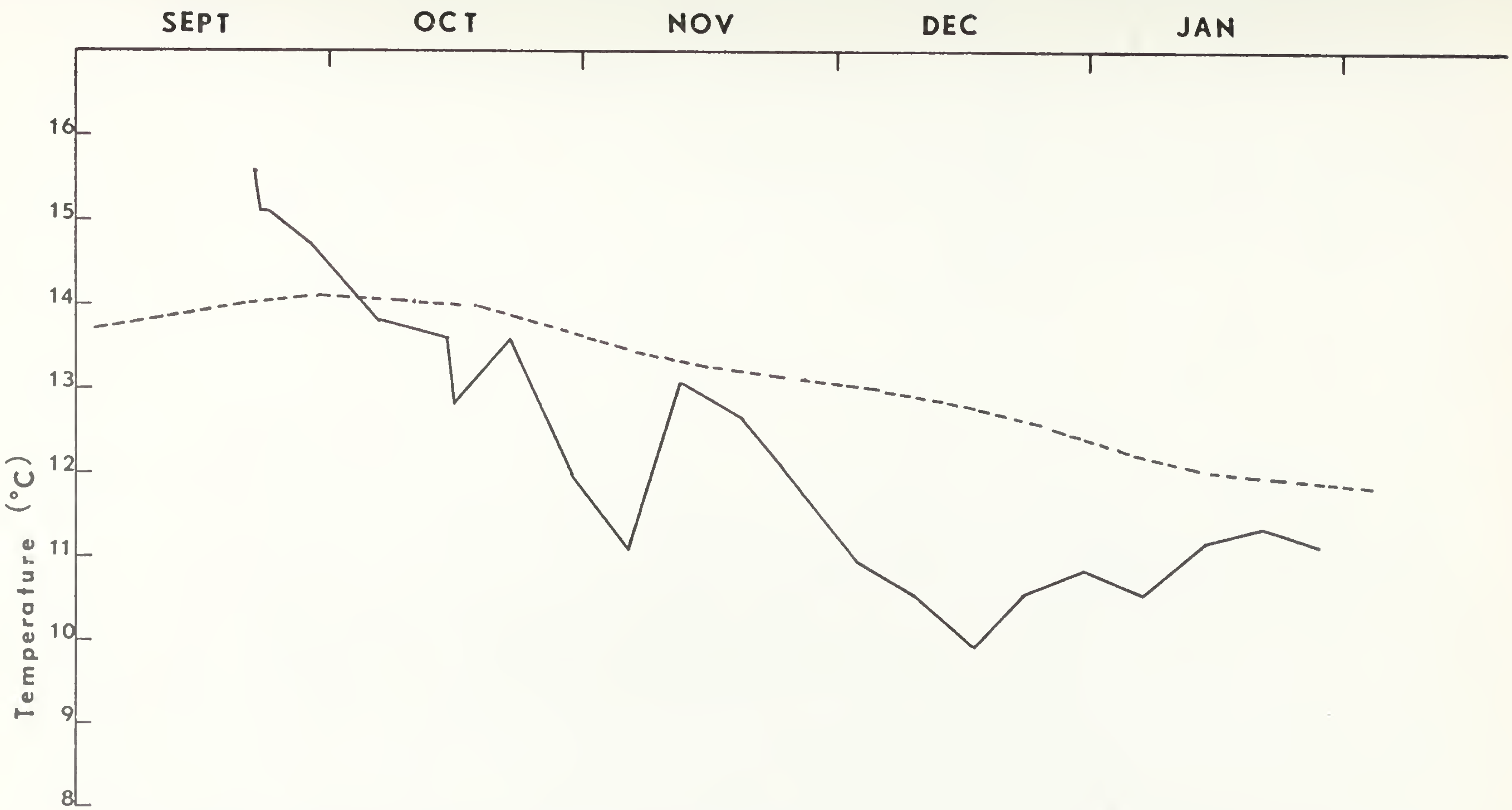

Fig 27. Changes in sea surface temperature at Station 5 (solid line) compared with long-term average computed by Lammers (dashed line).

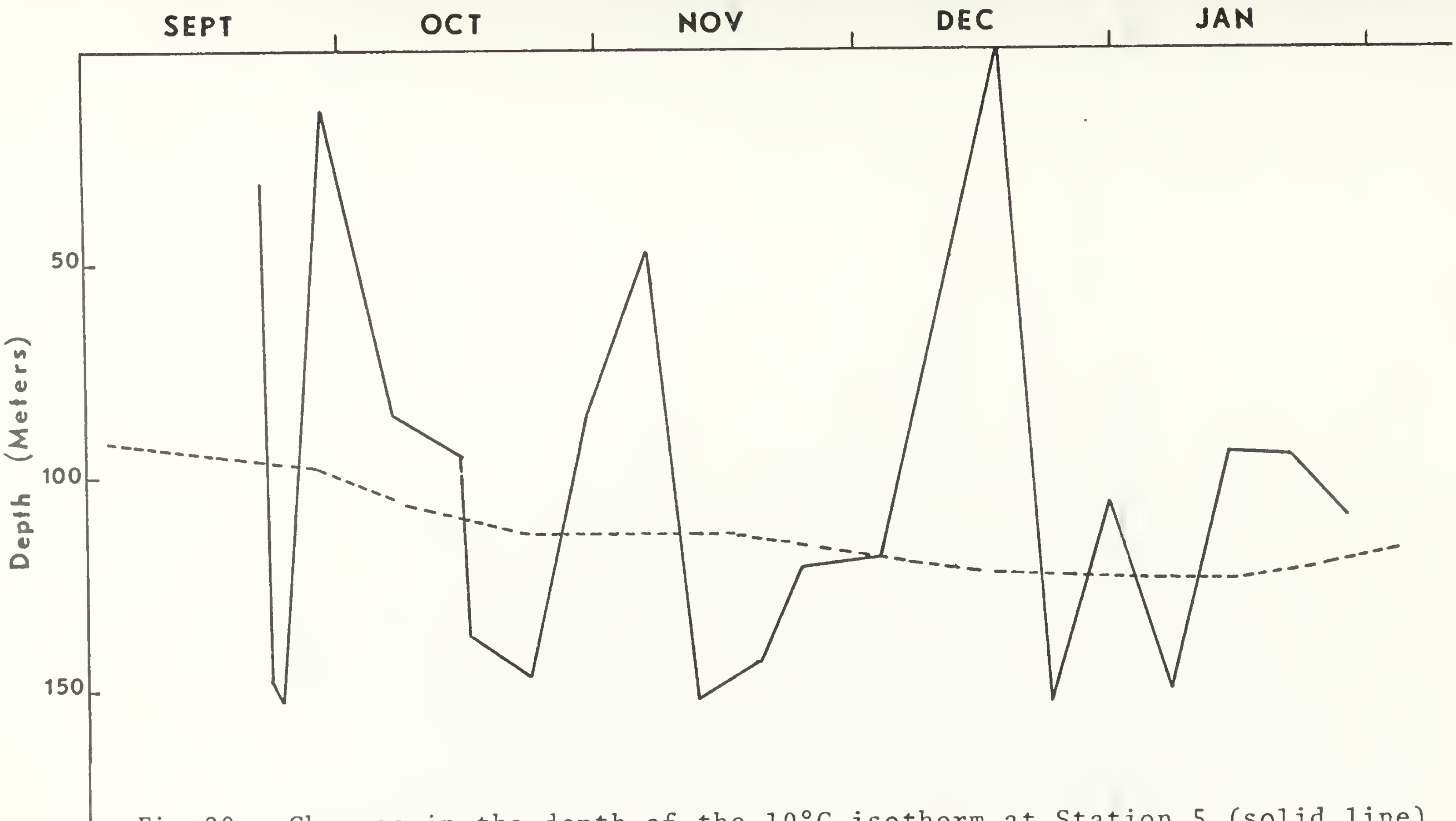

Fig 28. Changes in the depth of the 10°C isotherm at Station 5 (solid line) compared with the long-term average computed by Lammers (dashed line).

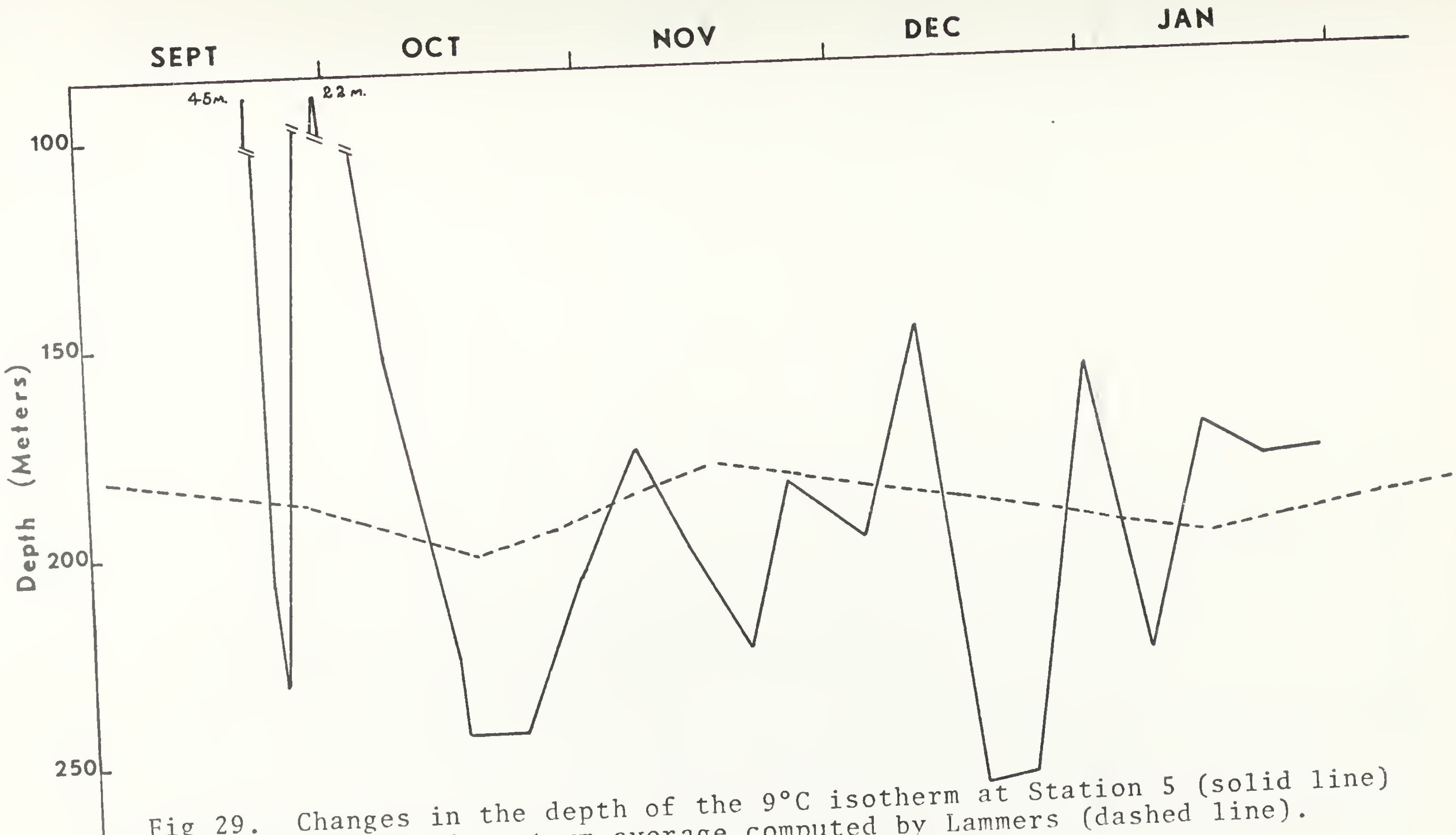

Fig 29. Changes in the depth of the 9°C isotherm at Station 5 (solid line) compared with the long-term average computed by Lammers (dashed line).

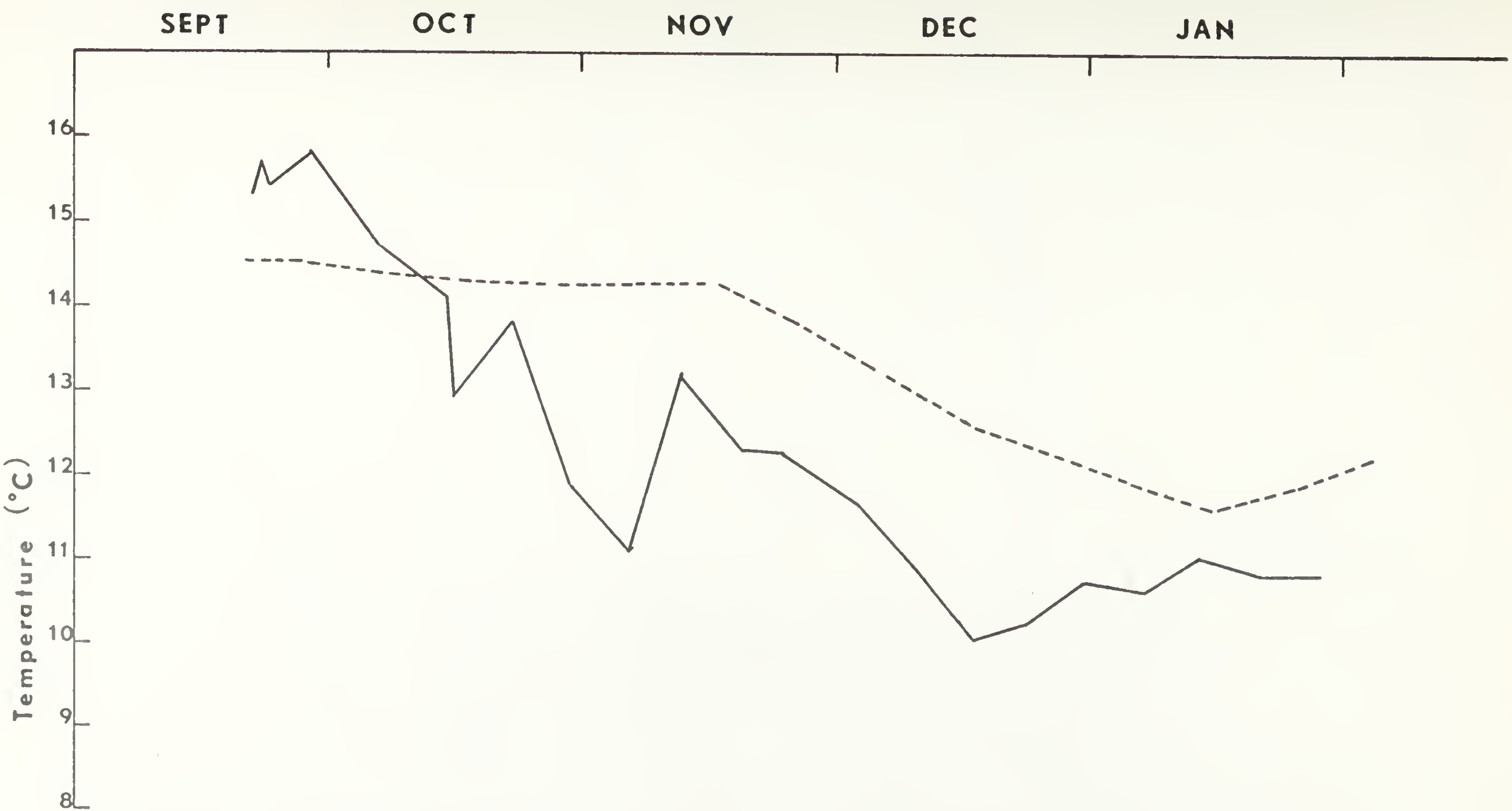

Fig 30. Changes in sea surface temperature at Station 8 (solid line) compared with long-term average computed by Lammers (dashed line).

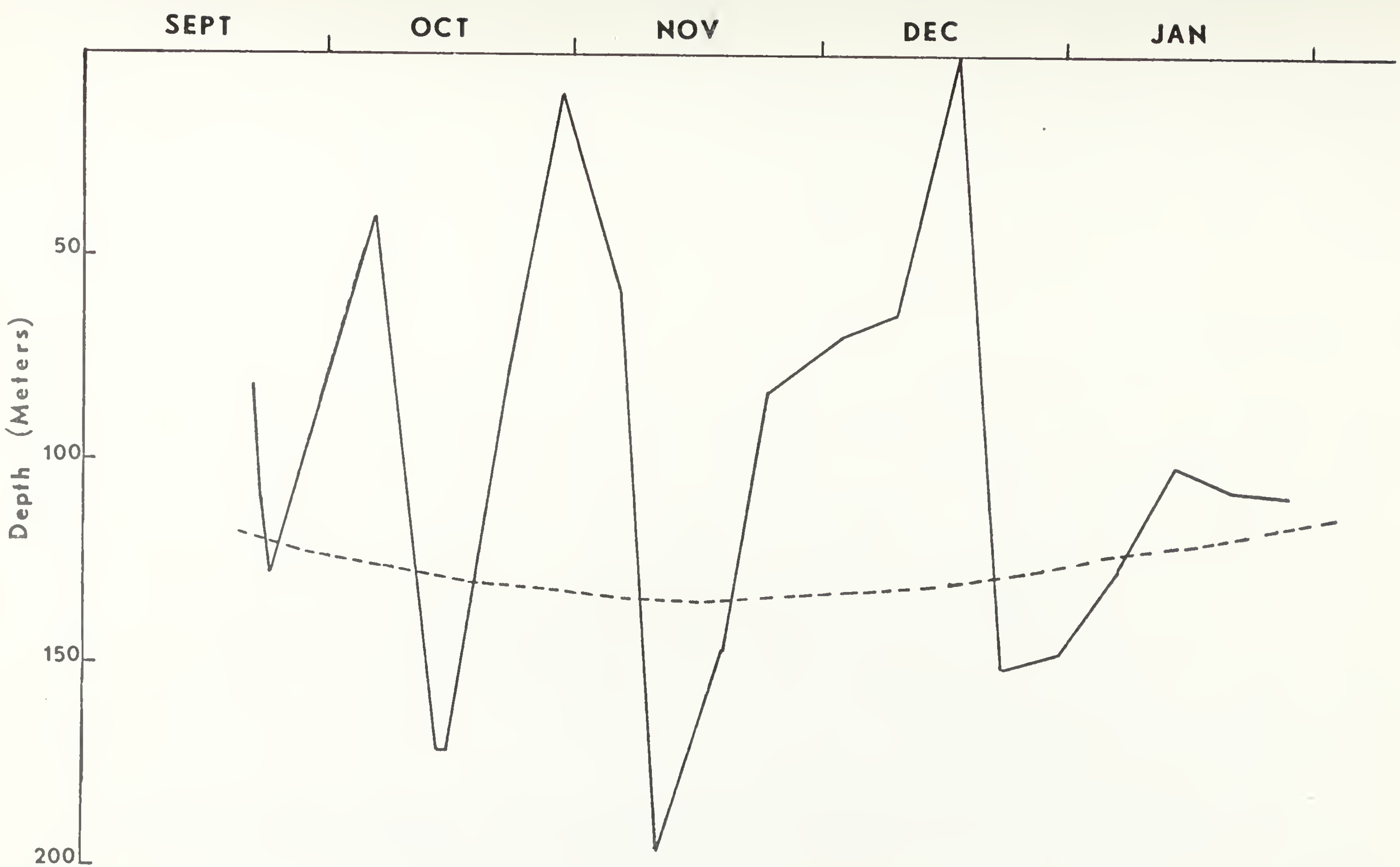

Fig 31. Change in the depth of the 10°C isotherm at Station 8 (solid line) compared with long-term average computed by Lammers (dashed line).

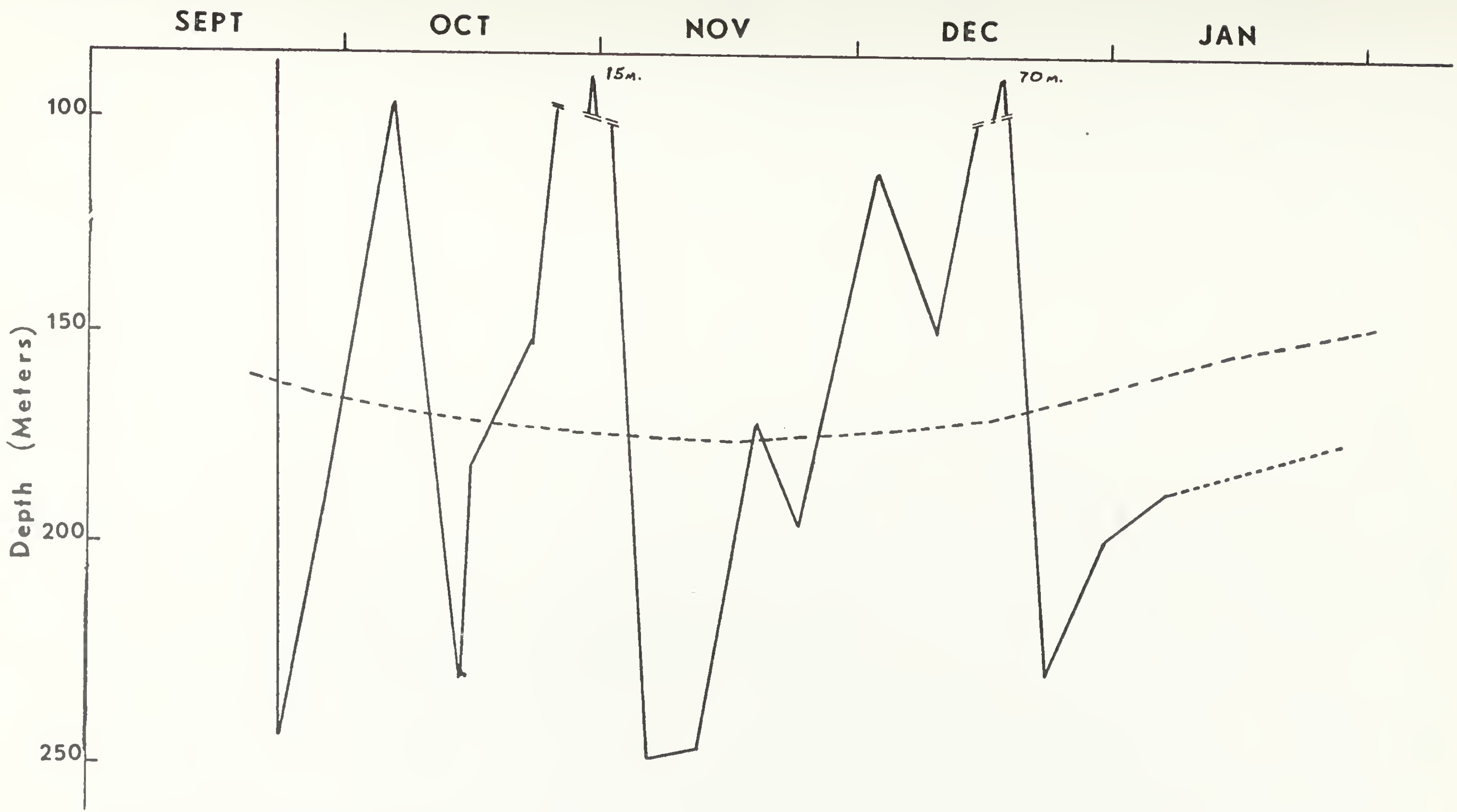

Fig 32. Change in the depth of the 9°C isotherm at Station 8 (solid line) compared with long-term average computed by Lammers (dashed line).

F. THERMAL TOPOGRAPHIC CONTOUR CHARTS

1. Sea Surface Temperatures

Figures 33 through 37 depict the monthly mean sea-surface isotherms over Monterey Bay during the period of study. The chart for September 1971 was, in fact, drawn from temperatures read during 21, 22, 23, and 28 September. Decreasing surface temperatures were observed from west to east with some warming along the eastern edge of the bay. While the bay surface temperature was nearly uniform at around 15.5°C, relative cool spots were observed at Station 6 in the north and Station 2 to the south. These cool spots were connected by a band of 15.0 - 15.2°C water which appeared in the center of the area during the end of September. At this time the upwelling was still weaker than the 1948-1967 mean would have indicated and the relatively cooler band may have been an artifact of the upwelling, trapped between the warmer oceanic surface water and the warmer water along the shore line.

During October the average bay temperature was approximately 2°C lower than at the end of September. Surprisingly, the isotherms representing water 2°C cooler than in September remained at nearly the same locations as in September, thus indicating uniform cooling throughout the bay. The cool band observed in September not only persisted but expanded and appeared as a cool tongue projecting into the center of the bay from the south. Upwelling was stronger than normal for

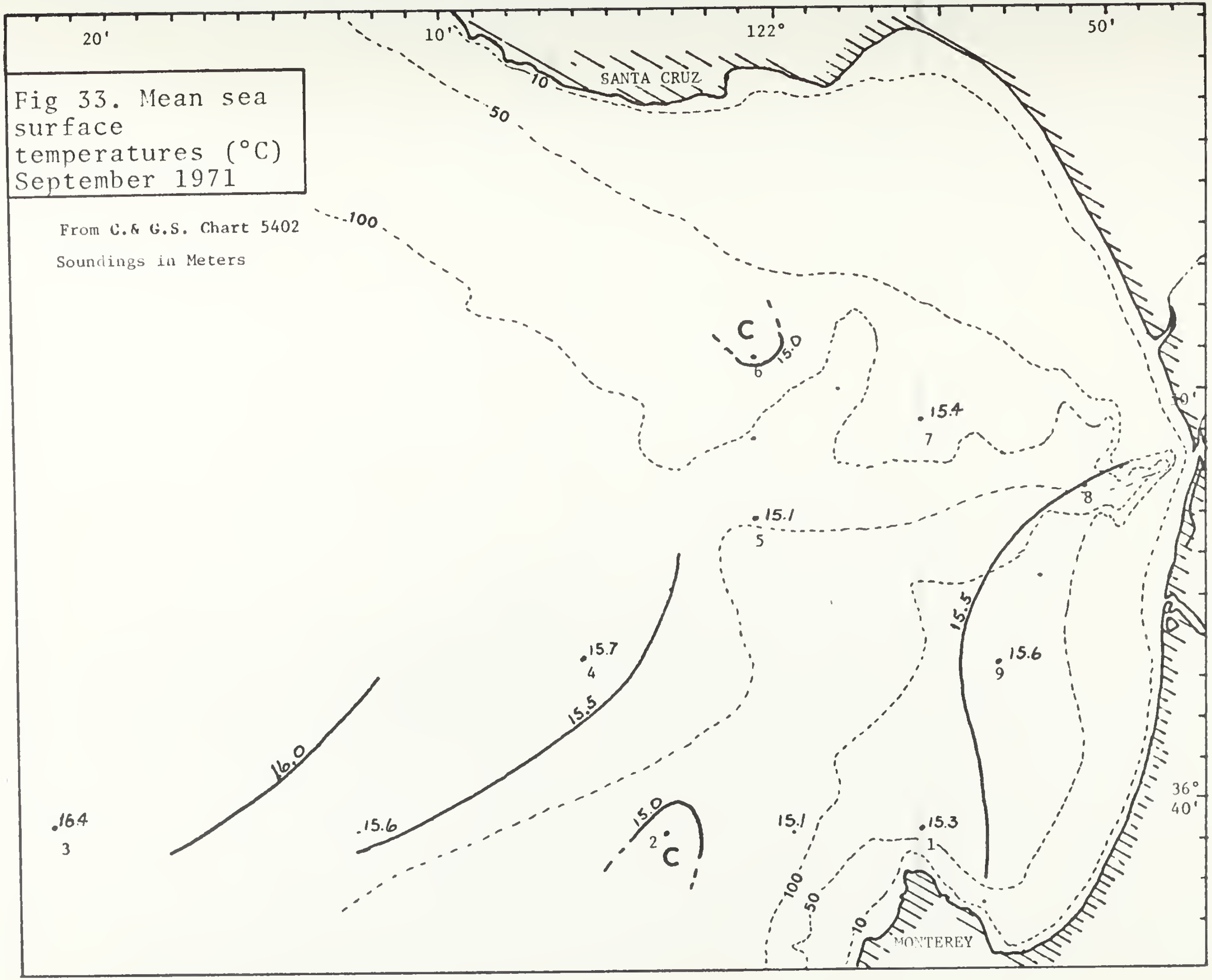

Fig 33. Mean sea surface temperatures (°C) September 1971

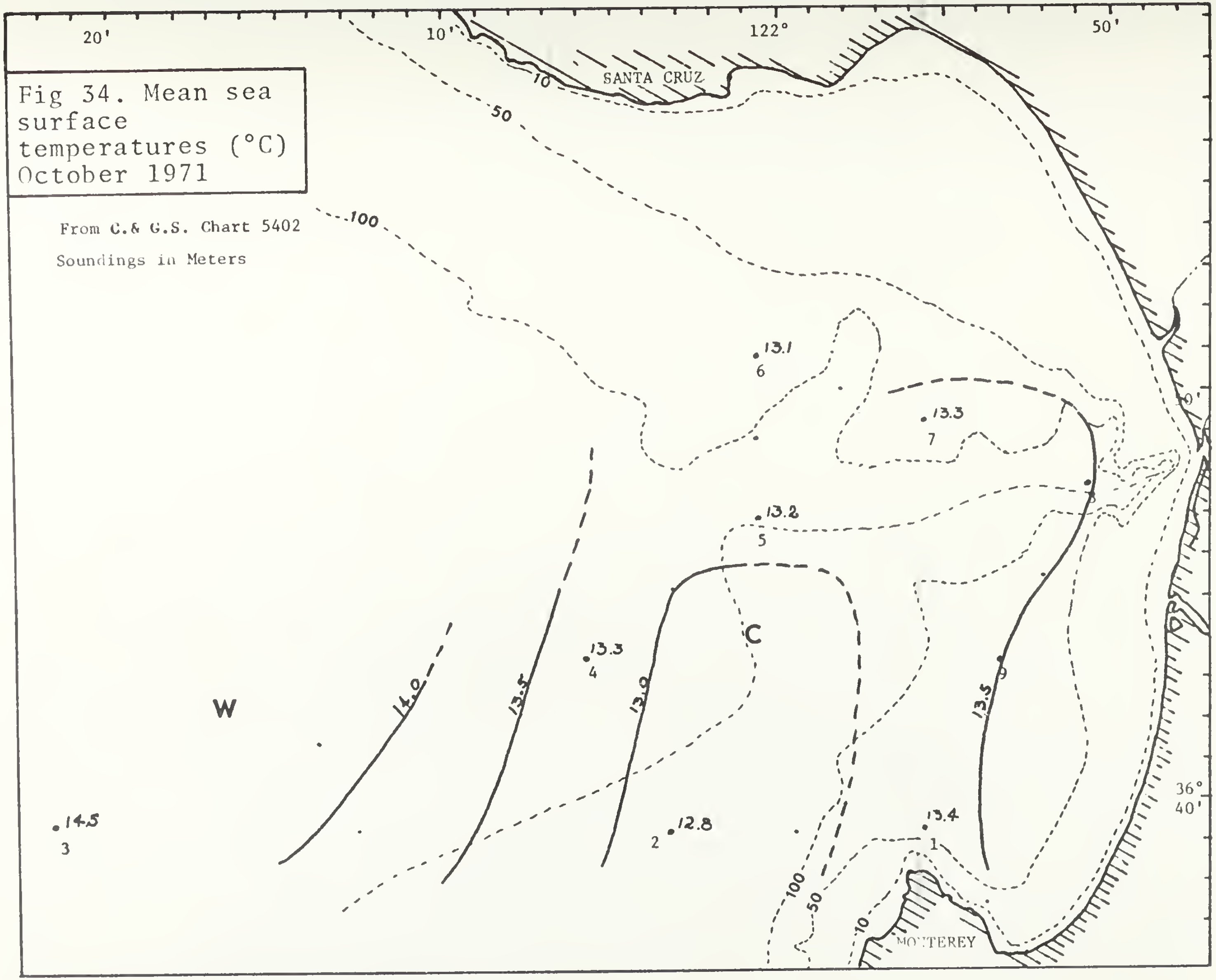

Fig 34. Mean sea surface temperatures (°C) October 1971

From C.& G.S. Chart 5402

Soundings in Meters

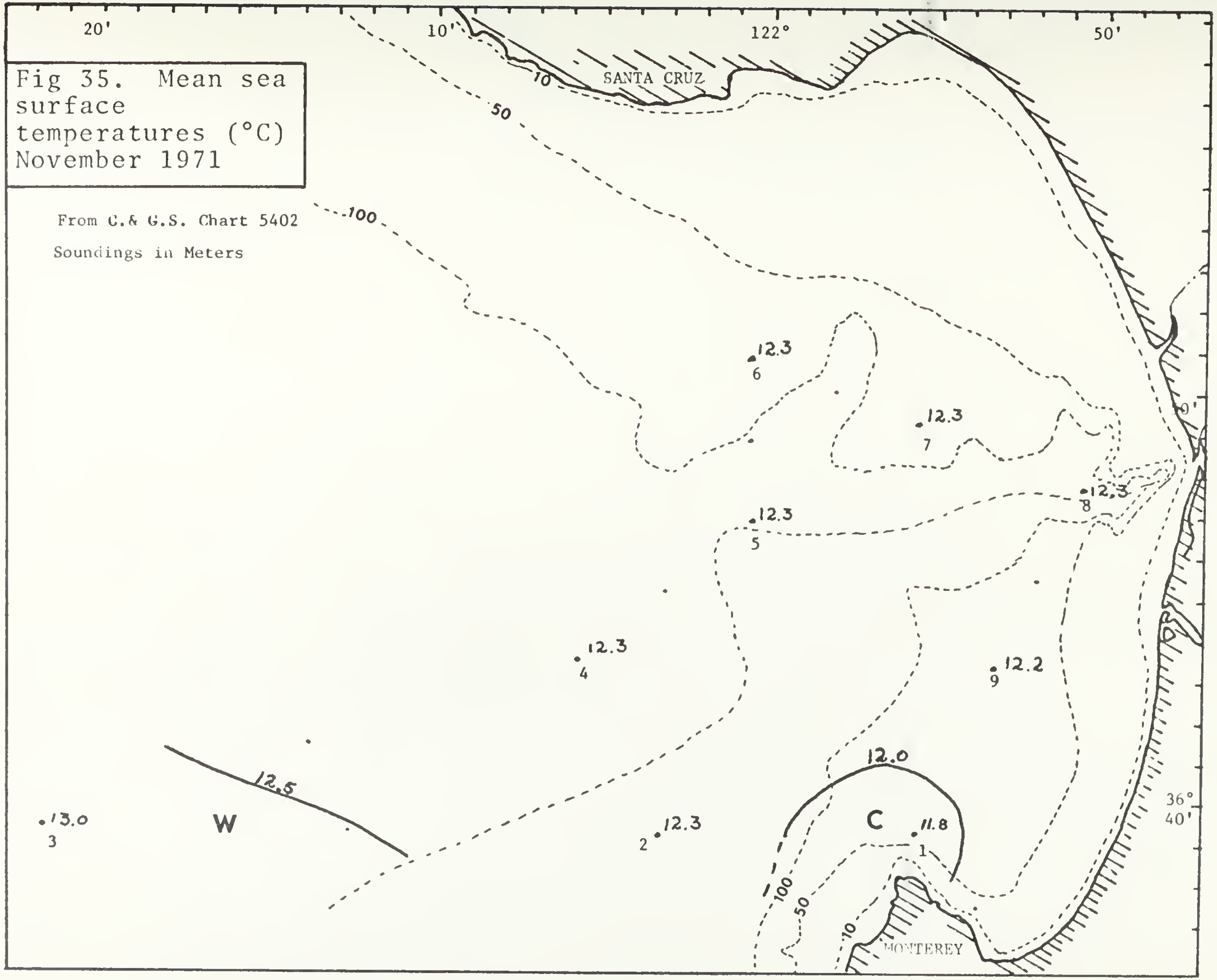

Fig 35. Mean sea surface temperatures (°C) November 1971

From C.& G.S. Chart 5402

Soundings in Meters

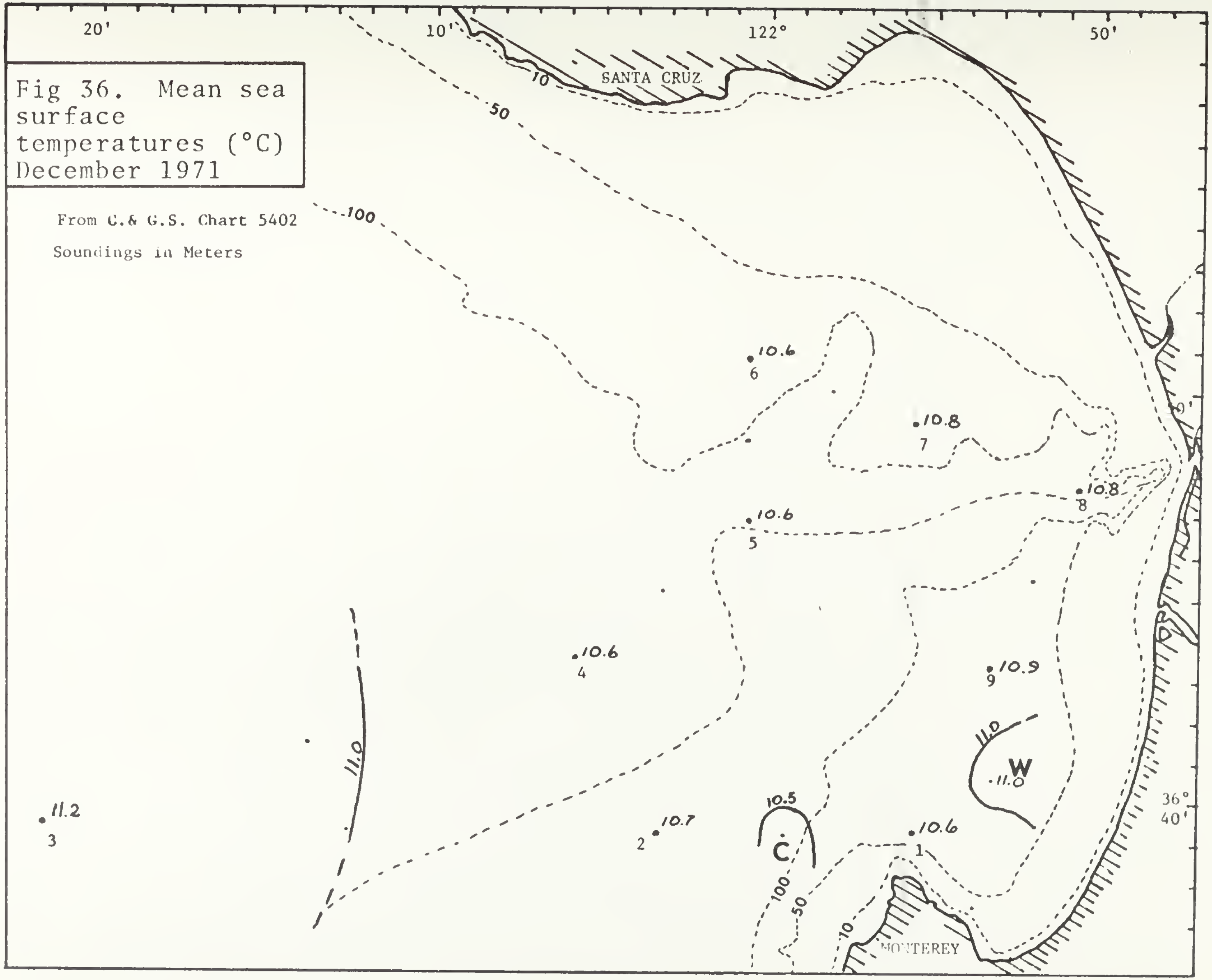

Fig 36. Mean sea surface temperatures (°C) December 1971

From C.& G.S. Chart 5402

Soundings in Meters

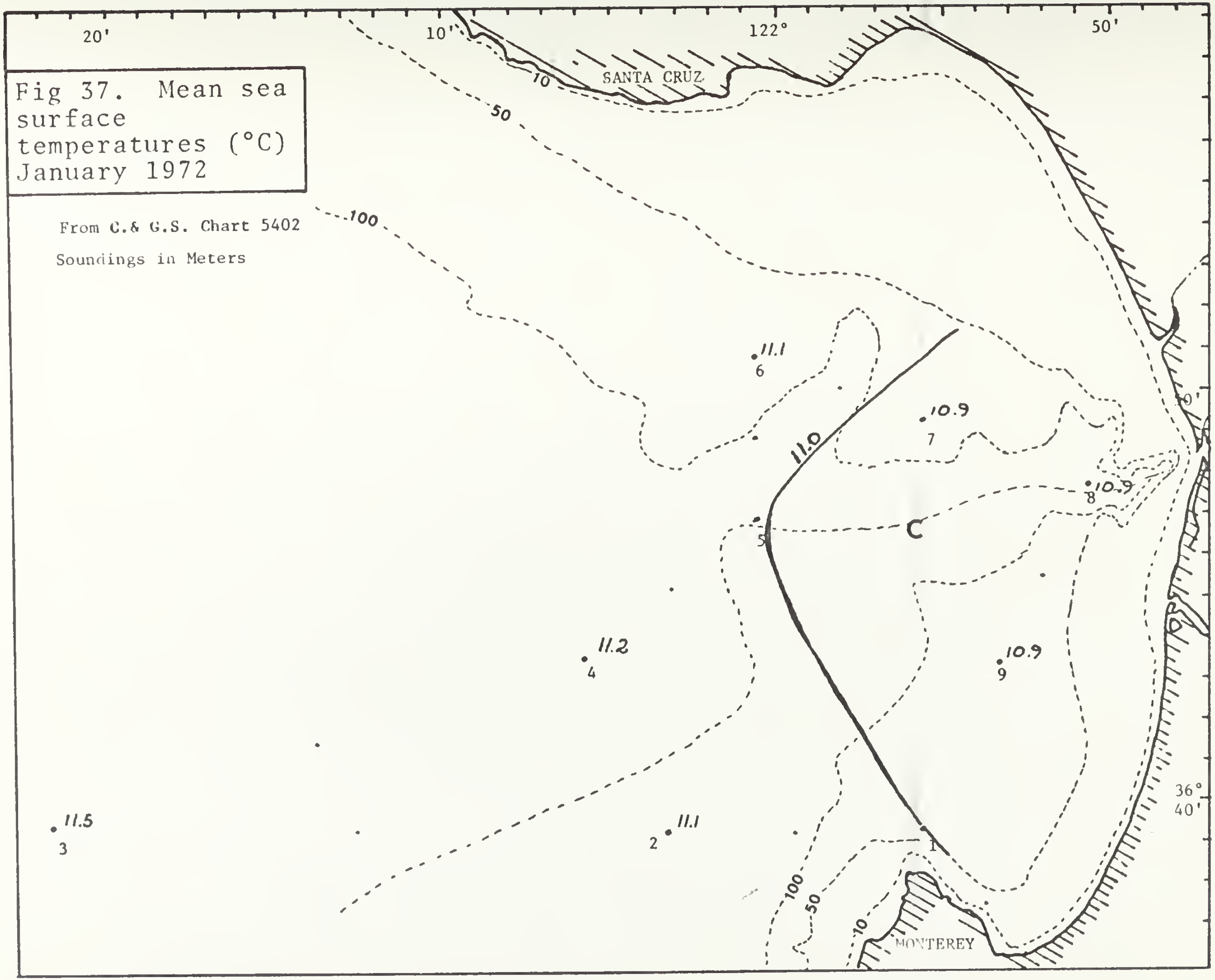

Fig 37. Mean sea surface temperatures (°C) January 1972

October, and a weak northward current was observed, from current velocity profiles, to roughly 30 meters during the first part of the mongh. The increased upwelling would perhaps account for the general reduction in the bay surface temperatures.

From October to November the surface of the bay cooled slightly and became much more nearly uniform with 12.3°C being the most common temperature. The cool tongue which had been prominent in October decreased in area and was found displaced to the east. Upwelling, although stronger than normal for the month, was weak.

December 1971 was still cooler than the preceding month, but was more uniform, having a temperature range between 10.5 and 11.0°C. Once again the coolest spot in the area was found between Stations 1 and 2. However, it was very small and the horizontal temperature gradient between this spot and Stations 1 and 2 was very small.

The month of January produced the least interesting surface thermal features observed during this research. The greatest difference in temperatures between a pair of stations was 0.6°C (between Stations 3 and 8). A trend toward surface warming was indicated as the mean 11°C isotherm was roughly 12 miles further into the bay than it had been the previous month.

2. Mean Topography of the 10°C Isotherm

The temperature in the upper 150 meters of the bay was of particular interest in that the vertical thermal

gradients have been useful in describing the three "seasons" of Monterey Bay. While several isotherms were observed, the vagaries of the 10°C isotherm were such that this isotherm could be observed at most of the stations during the period of investigation. The mean topography of this isothermal surface for the end of September and for the entirety of the next four months is plotted in Figs. 38 through 42. The contours are in 10-meter invervals, larger numbers indicating a greater depth for the isotherm. Where the isotherm was deep the water column through the layer of migration would be expected to be warmer, and thus less dense, than where the isotherm was near the surface.

These contour charts were of further interest in that a geostrophic current could be inferred from the relative difference in temperature in the water between two adjacent water columns. For example, if the western station of a pair of stations has a cooler water column, and the same reference level is used for both stations, then a northward flowing current can be inferred to exist between them (in the Northern Hemisphere).

Because it reflects the depths at which greatest density changes seemed to occur, the 10°C isotherm chart for September is considerably more interesting than the sea surface temperature chart for the same period. A relatively cool spot shown by the 10°C topography chart, similar to that found on the surface at Station 2, was observed between

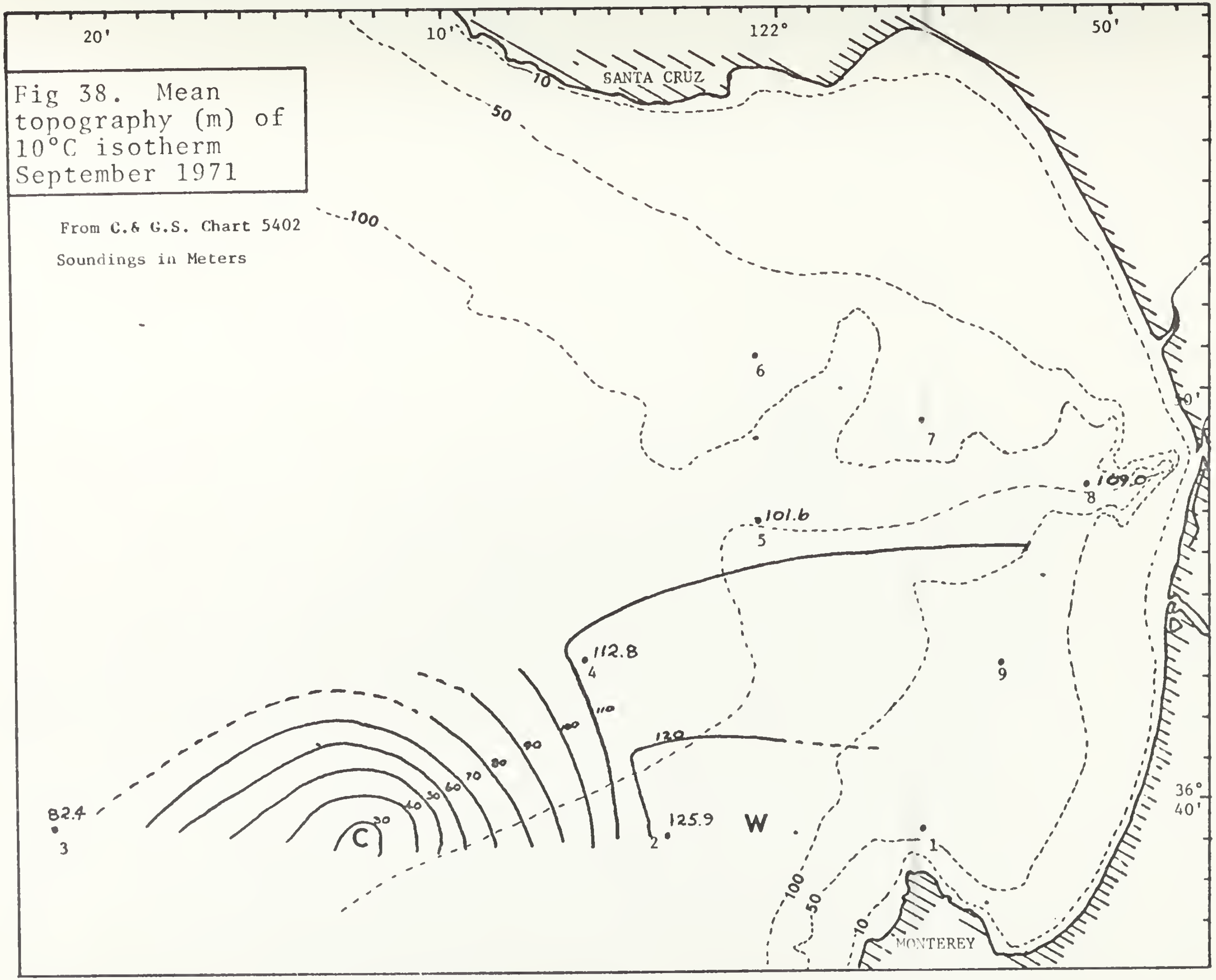

Fig 38. Mean topography (m) of 10°C isotherm September 1971

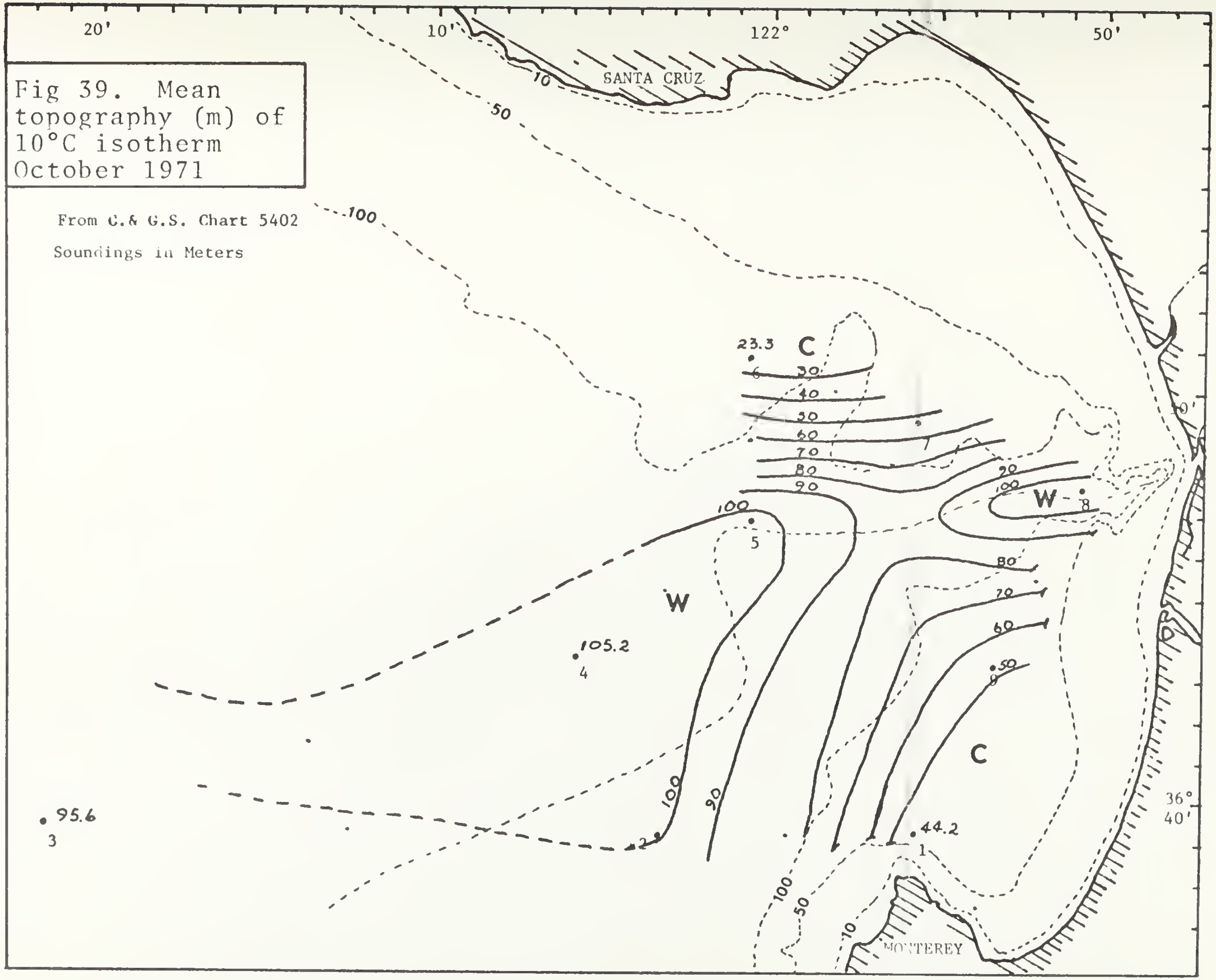

Fig 39. Mean topography (m) of 10°C isotherm October 1971

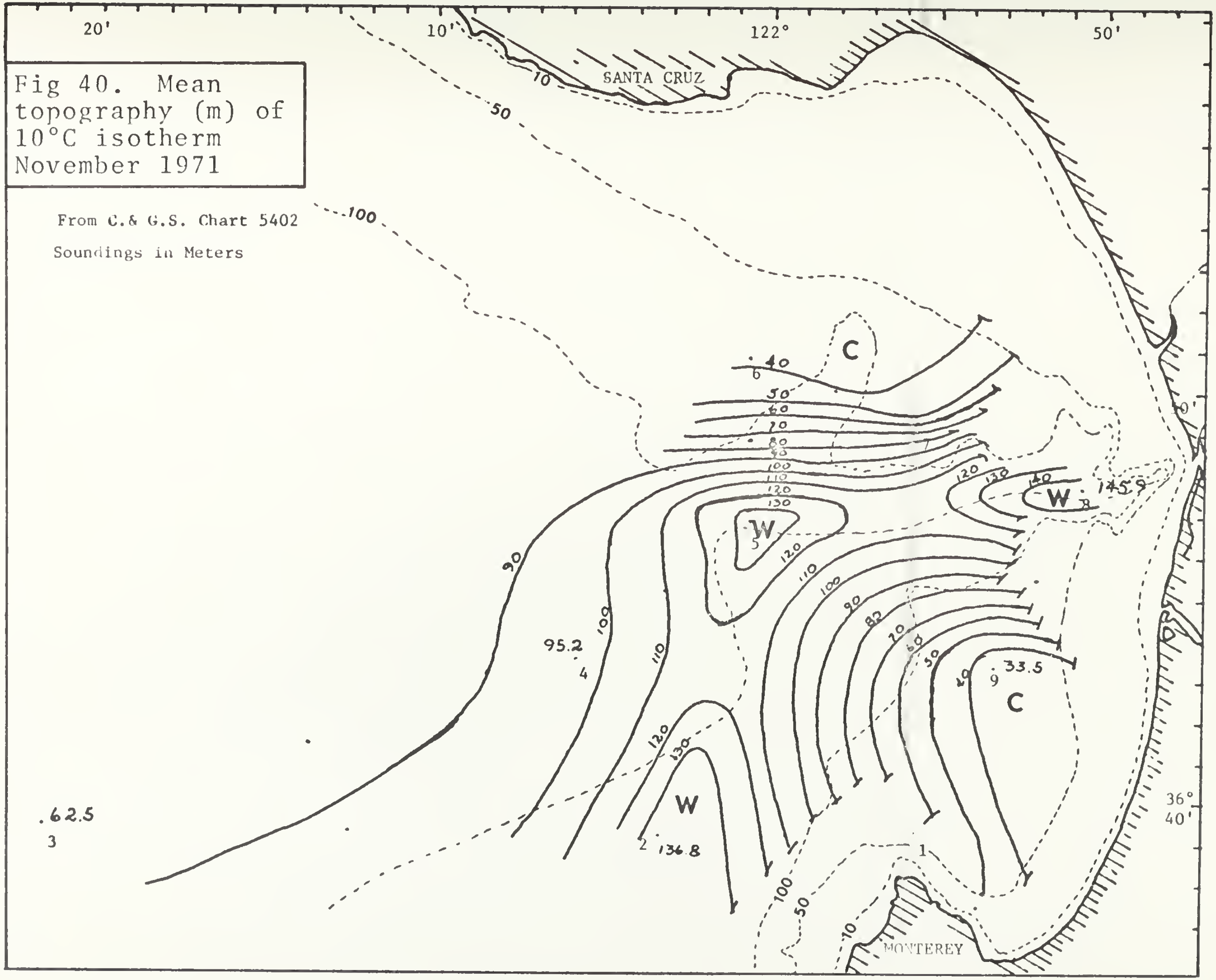

Fig 40. Mean topography (m) of 10°C isotherm November 1971

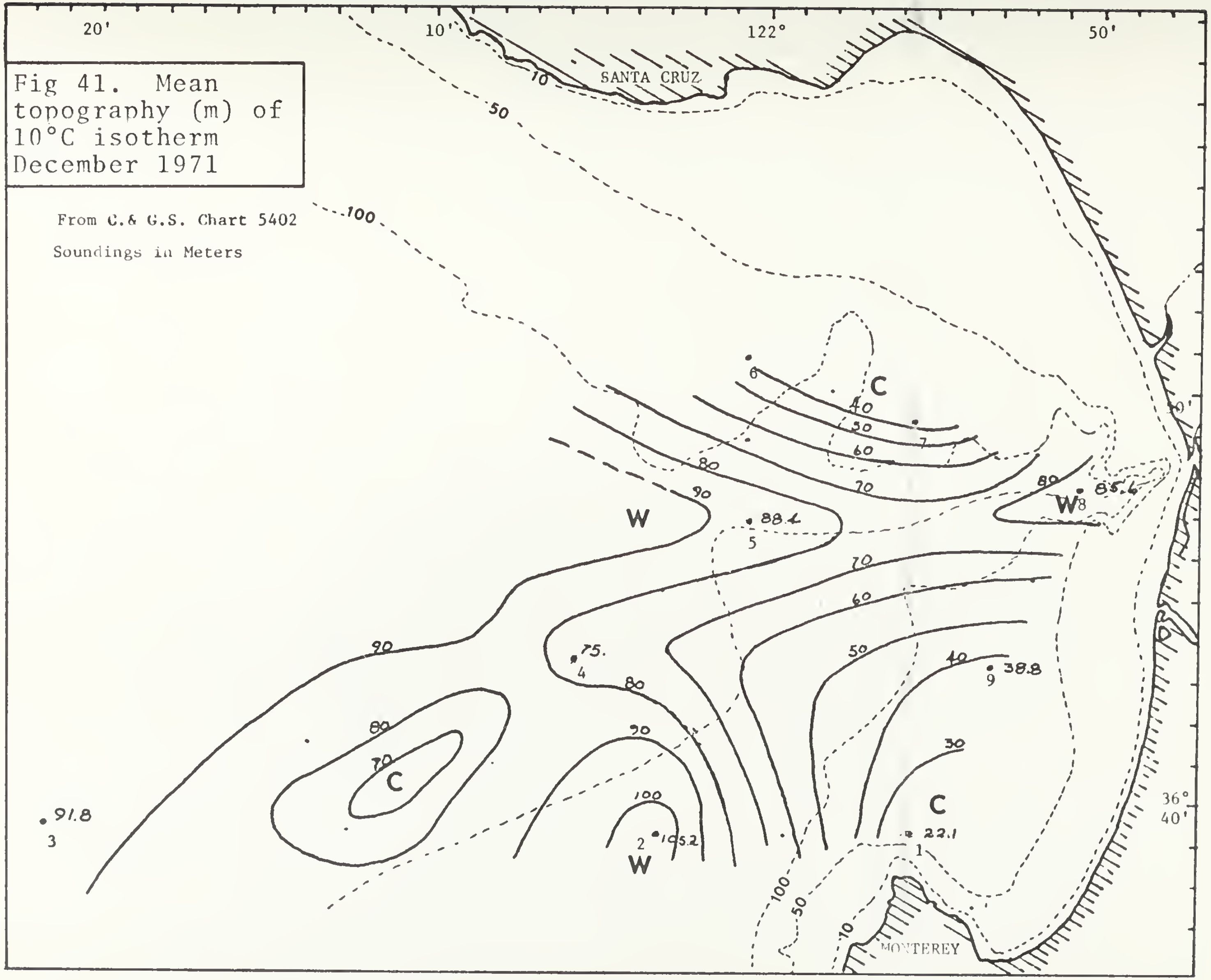

Fig 41. Mean topography (m) of 10°C isotherm December 1971

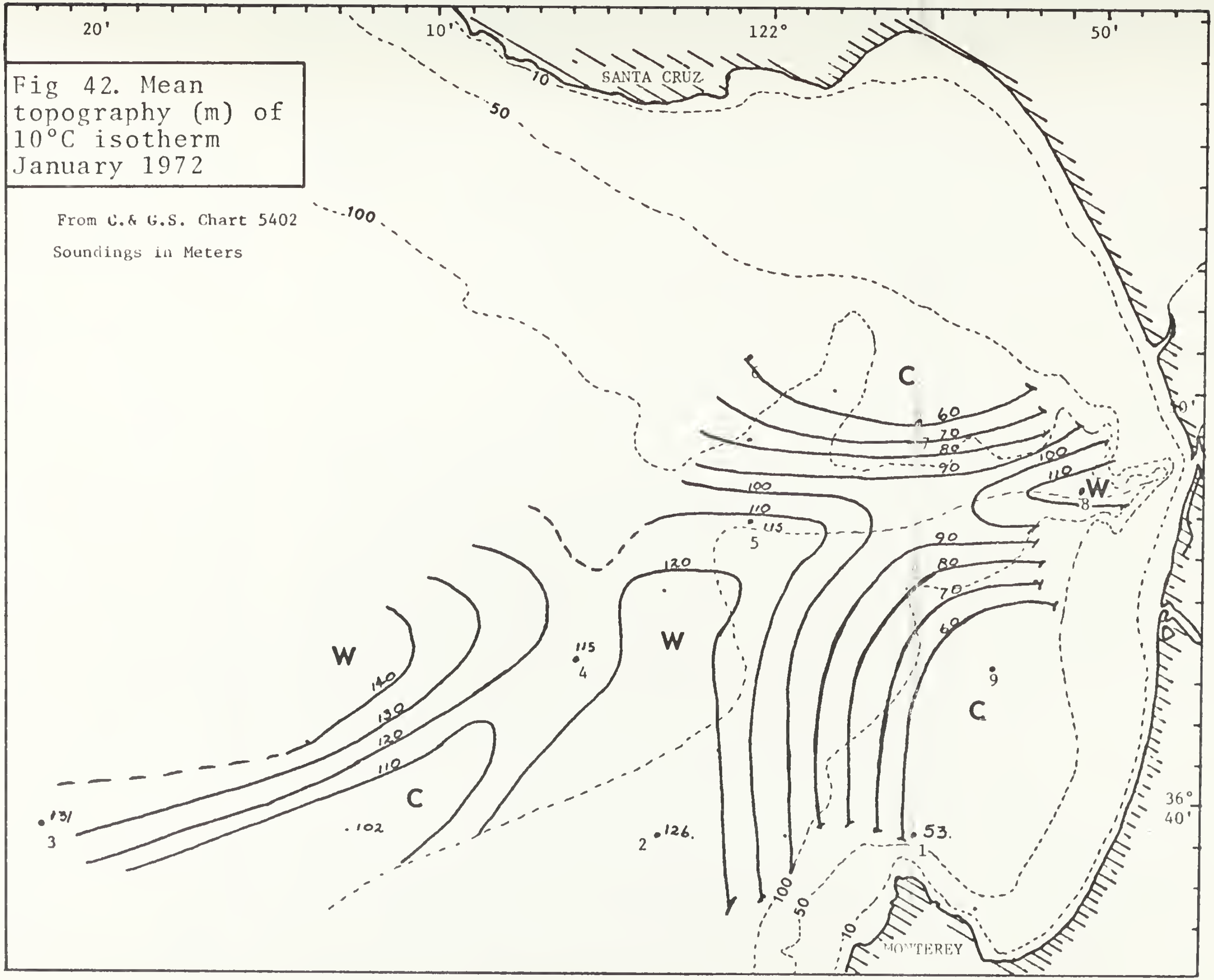

Fig 42. Mean topography (m) of 10°C isotherm January 1972

Stations 2 and 3. This spot would indicate a center of an anticyclonic eddy or a current loop with water moving northward near the coast and then turning to the west and southwest. Little eastward current could be inferred from the weak north-south topographic gradient observed in the warm waters over the southern shallows area of the bay.

During October a tongue of warm water was present over the axis of the canyon as shown by the 10°C isotherm at about 100 meters. This warm tongue was opposed by another smaller pool of warm water which appeared at the head of the canyon. The shallow areas to the north and south of the canyon were, during October, relatively cooler than they had been the previous month. It will be recalled that during October the anomalous surge in the upwelling reached its maximum. The presence of warm waters along the canyon axis implied that the upwelling cool water rose along the sides of the canyon and then spread out over the shallows allowing warmer water to remain in near-surface layers over the canyon.

The slopes of the 10°C surface indicate a current loop flowing in a clockwise direction in the center of the bay. Current velocity profiles between Stations 2 and 3 for October show a slight southerly current at around 50 meters and a net northward transport from the surface to 900 meters. It is doubtful that the 50-meter current caused the indicated anticyclonic circulation. However, it did not seem unreasonable to assume that the tongue of warm water extending into

the canyon was a result of advection from the south (on the order of 0.04 Sverdrups) between Stations 2 and 3.

November 1971 data showed similar contours to those observed in October, but the warm tongue which had extended into the canyon from the west was now compressed into a band of warm water which followed the canyon axis north and then east with pools of warm water appearing at Stations 2, 5, and 8. The compressing of the warm tongue into a band appears to have been caused by a southward advection of cooler water into the bay. Current velocity profiles indicate that at least during the end of November a southward advection having velocities on the order of 12 cm/sec did occur between Stations 2 and 3 at about 75 meters. This may have reduced the horizontal extent of the warmer water. The net northward advection between Stations 2 and 3, which first appeared in October, persisted and would seem to account for the warm strip which followed the canyon axis. It will be recalled that the upwelling was very weak in November. The steeper 10°C isothermal surface was thought to be a result of increased advection of warm water in the slightly stronger northward mass transport between Stations 2 and 3.

The 10°C isothermal surface picture for December shows a departure from the previous two months. The primary agent for this change seems to have been the advection of relatively warmer water from the west. This warmer water feeds into the canyon axis at about Station 5, and allows

the warm strip from the head of the canyon to persist. It also drove the earlier advected cool water into the bay and formed a pool of cooler water between Stations 2 and 3. From this pool a ridge developed which prevented the warmer water around Station 2 from reaching up into the canyon around Station 5.

The upwelling index was at the minimum for the year in December. While there was some southward advection, and further general atmospheric cooling, the warm water is attributed to an influx of oceanic water and Davidson Current advection. While it would not have been expected to have oceanic water and Davidson Current water coexisting in the Bay, the oceanic water was in a relatively thin layer, and the Davidson Current water, while certainly present, was diminished by the anomalous upwelling in October and November.

In January 1972 the Davidson Current reached its maximum for the duration of this research. The current velocity profiles clearly show a northward transport from the surface to at least 900 meters, and warm water pushed up the canyon axis to the warm strip which had remained between Stations 5 and 8. While the words "warm" and "cool" are used in reference to the average temperatures of the upper layers, the surface temperature of the bay remained essentially as it had in December (about 11°C). The vertical thermal gradient from the surface to 100 meters was less than 1°C, so the upper 100 meters were relatively warm.

G. CHANGES IN TEMPERATURE-SALINITY CURVES AT STATIONS 2 AND 3

A series of representative temperature-salinity curves for Stations 2 and 3 were prepared for the period of study (see Figs. 43 through 47). The T-S curves clearly represent the North Pacific Sub-Arctic Water mass as described by Sverdrup, et al. (p. 713). Although the same water mass was present throughout the duration of the study, the T-S curves did change, especially in the upper 100 meters. It is interesting to note that below 10°C there was relatively little change in the shape or displacement of the station T-S curves.

During the end of September 1971 the upper 50 meters in the water column at Station 3 had an average salinity of about 33.20 ‰, about 0.32 ‰ less saline than Station 2. Station 3 was, on the average, about 1.4°C warmer than Station 2 which averaged 12.4°C. From 50 meters to 1,000 meters both curves could be approximated by a straight line connecting T = 12°C, S = 33.55 ‰ and T = 4.5° and S = 34.4 ‰. On 23 September a body of more (0.4 ‰ saline water was observed at Station 3 at a depth of 400 meters; the temperatures at 2 and 3 being similar. This more saline water at Station 3 was found between 200 and 800 meters and is indicative of the California Countercurrent bringing in less saline water of more equatorial origin.

By the first week in October the more saline water at Station 3 between 200 and 800 meters had disappeared, and

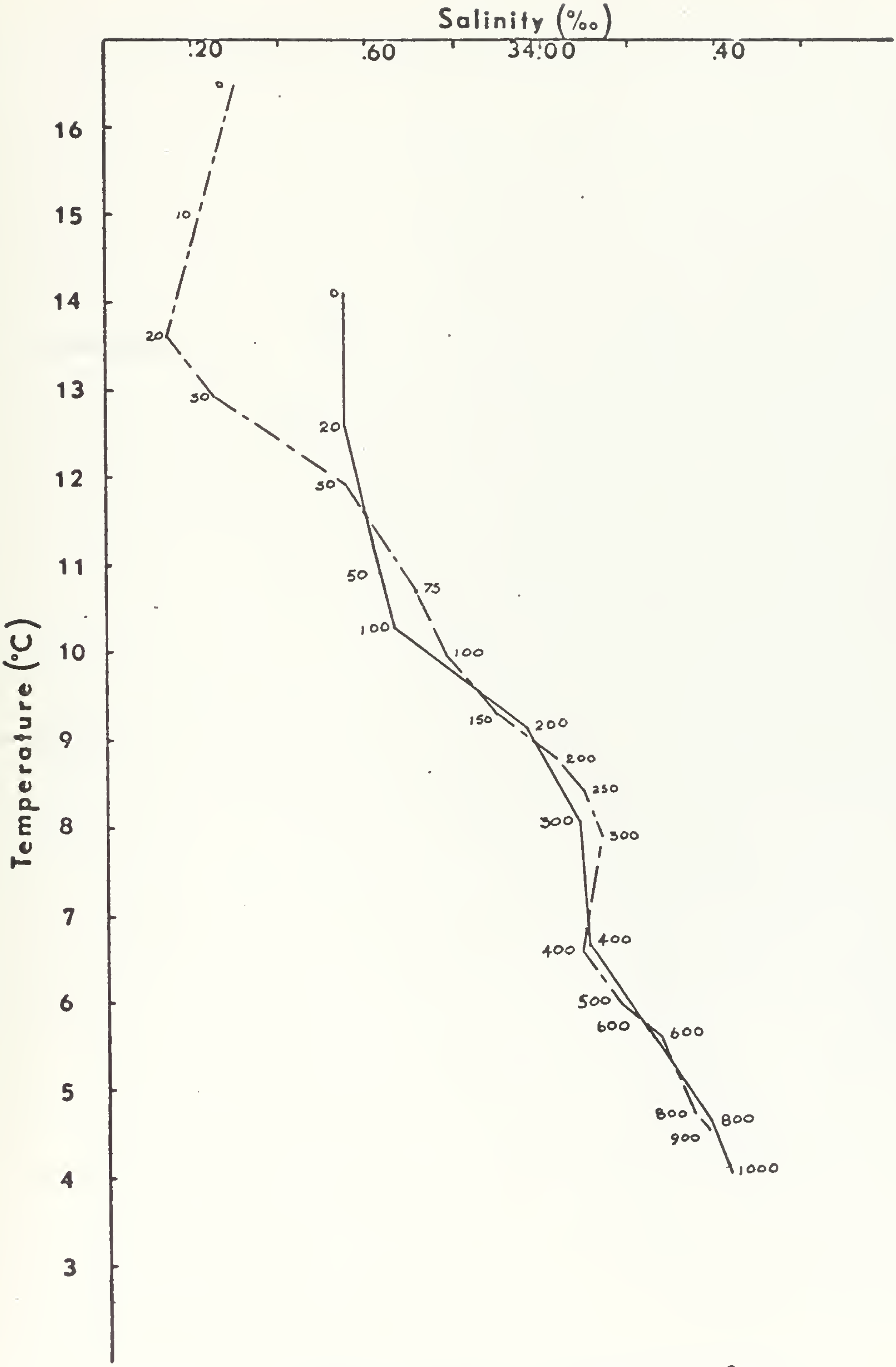

Fig 43. Representative T-S curves for September 1971 Station 2 (solid line) and Station 3 (dashed line). Depths of points in meters.

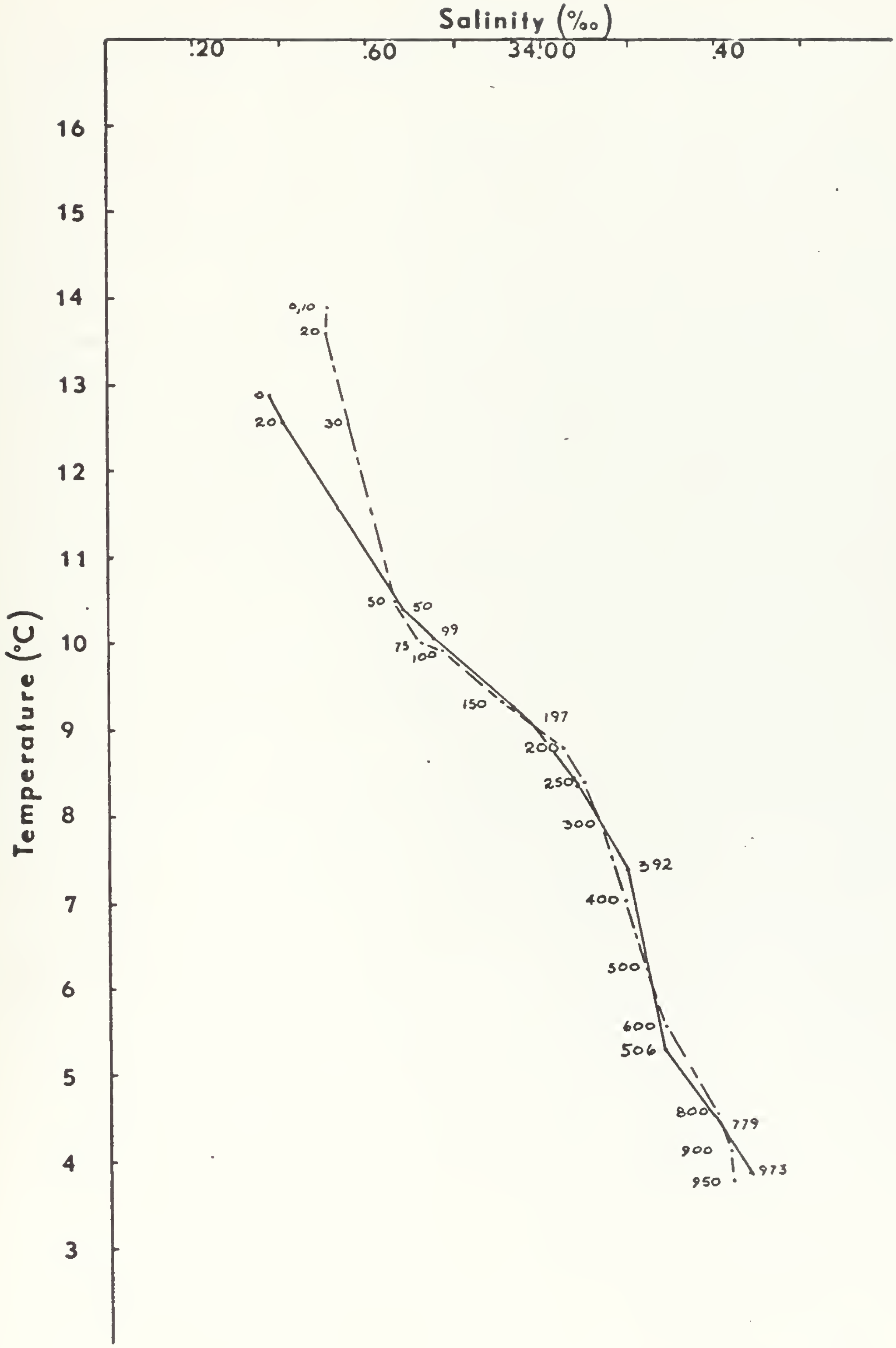

Fig 44. Representative T-S curves for October 1971 Station 2 (solid line) and Station 3 (dashed line). Depths of points in meters.

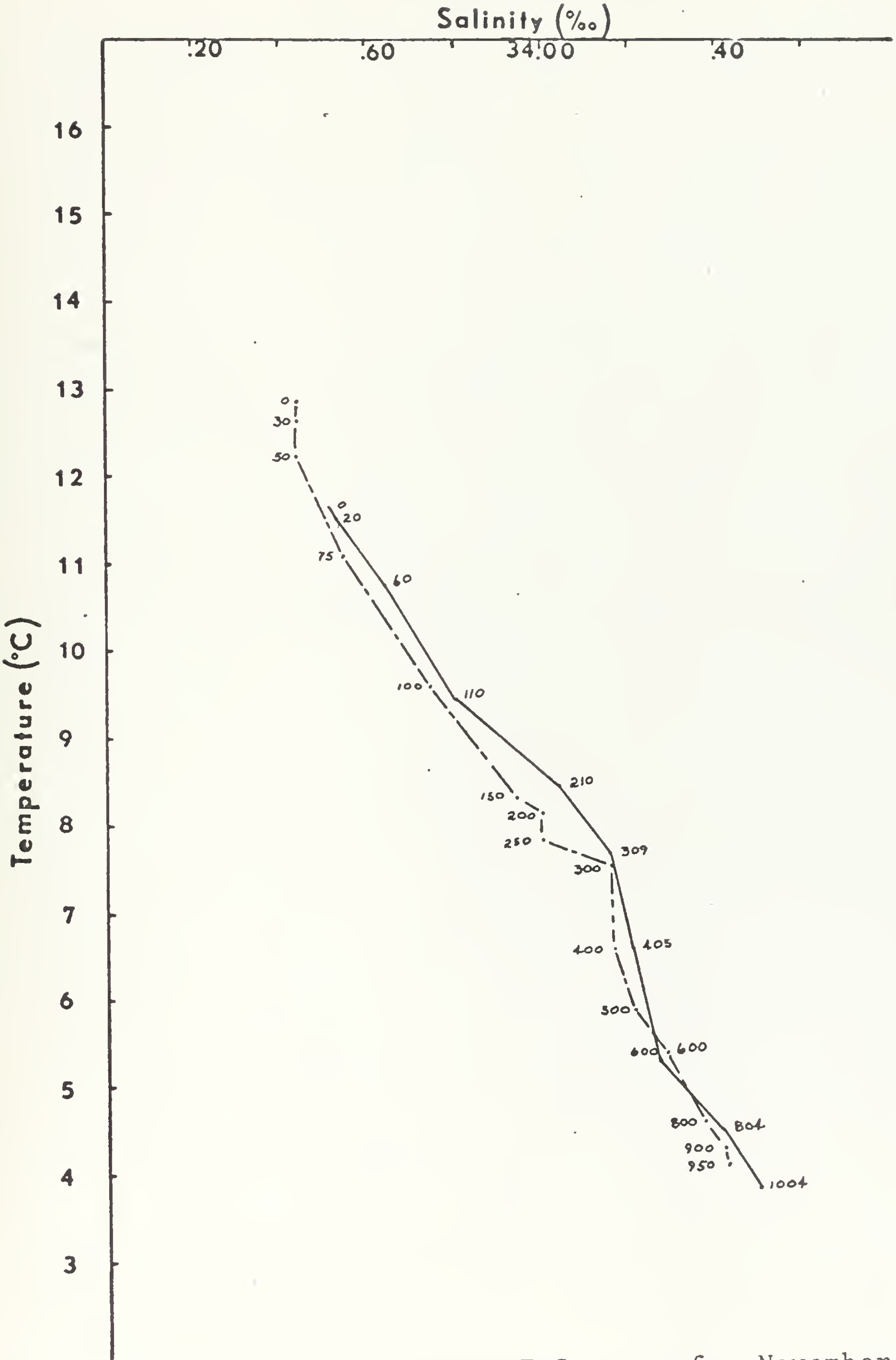

Fig 45. Representative T-S curve for November 1971 Station 2 (solid line) and Station 3 (dashed line). Depths of points in meters.

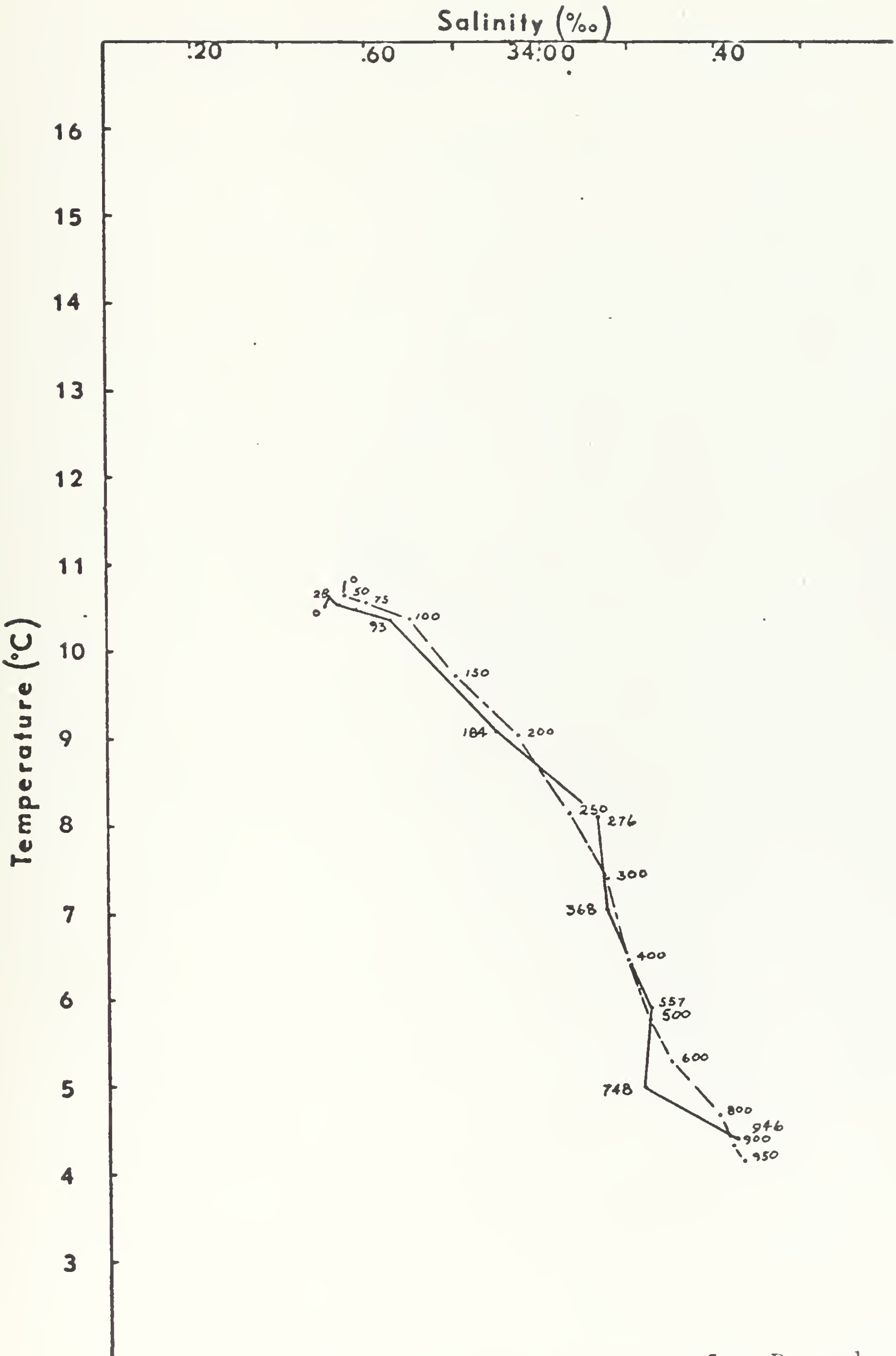

Fig 46. Representative T-S curve for December 1971 Station 2 (solid line) and Station 3 (dashed line). Depths of points in meters.

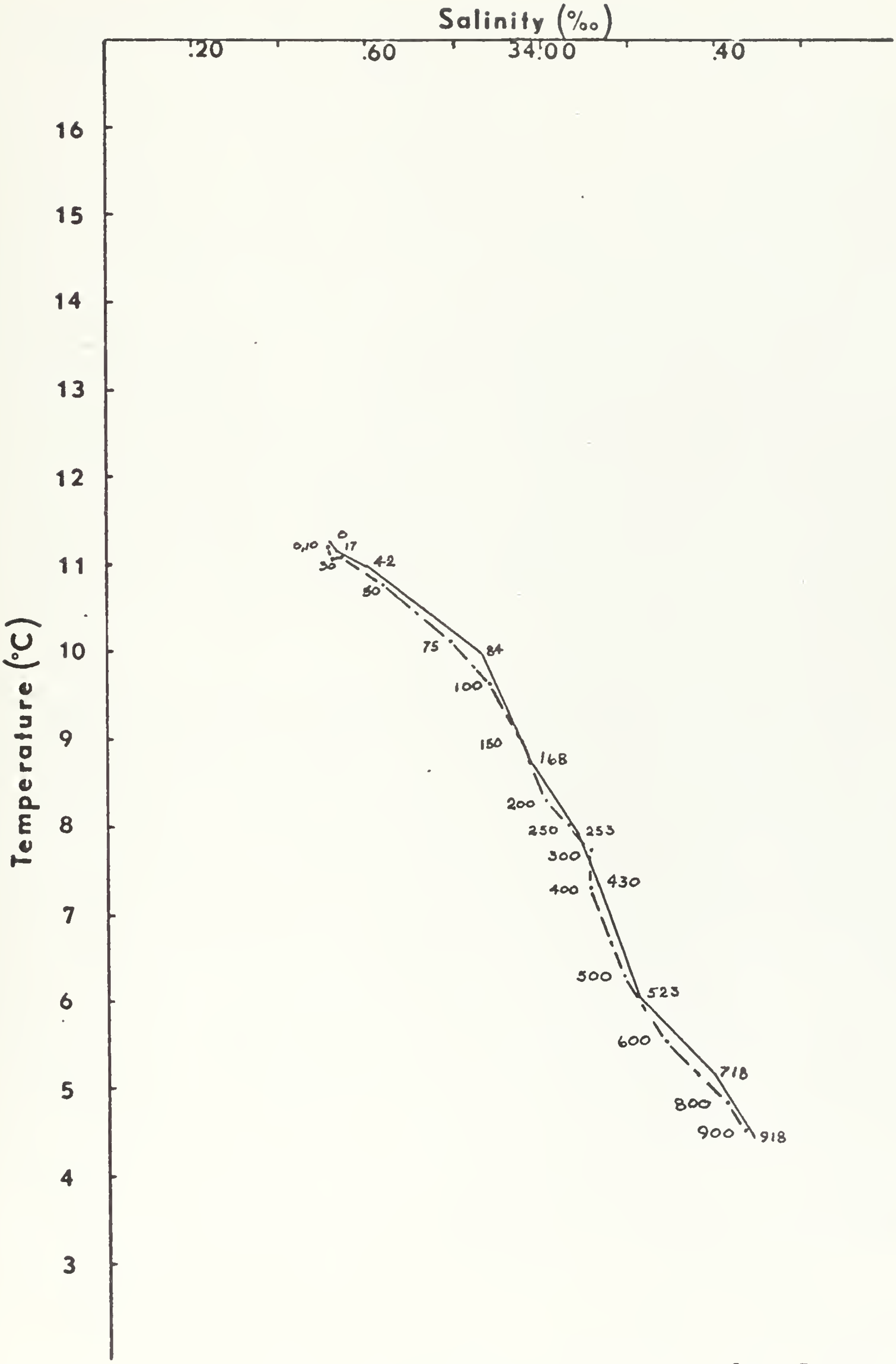

Fig 47. Representative T-S curves for January 1972 Station 2 (solid line) and Station 3 (dashed line). Depths of points in meters.

on the average the upper 50 meters at Station 3 were 2°C warmer and 0.3 °/₀₀ more saline than the same layer at Station 2. By 14 October Station 2 was relatively unchanged, while at Station 3 there was an influx of less saline water between 20 and 300 meters and an increase in the salinity at depths less than 20 meters. The salinity at Station 3 at a depth of 50 meters was approximately 0.4 °/₀₀ less than that on 6 October. While it was most common for the upper 50 meters at Station 3 to be warmer and less saline that Station 2, on 22 October it was observed that Station 3 was roughly 0.1 °/₀₀ more saline and 0.5°C warmer than Station 2.

Station 2 remained essentially unchanged throughout November 1971, and Station 3 was, for the most part, the same as Station 2 on 19 November. Between 19 and 24 November a body of considerably less (0.45 °/₀₀) saline water was advected into the area of Station 3, primarily in the upper 75 meters, but was detectable down to 275 meters.

Throughout December 1971 and January 1972 there was little difference in the T-S curves for Stations 2 and 3; the principal changes in the curves appearing in the upper 75 to 100 meters where the water temperature reached a minimum of about 10.0°C by the end of December. By the end of January the temperature in the upper 75 meters "rebounded" to around 11.5°C, the late November values.

H. CURRENT VELOCITY PROFILES

As mentioned previously, an objective of this research was to investigate the north-south current component between Stations 2 and 3 just west of Monterey Bay and to relate changes in the bay to this current. Data was collected at these stations by means of Nansen casts to 1,000 meters and/or with an automatically sensing STD. An IBM 360 computer system was then used with a modified NPS Department of Oceanography geostrophic program to process the data and do the dynamic calculations necessary to give the geostrophic current velocities at standard depths from the surface to a reference level of 1,000 meters. When the cast depth was less than 1,000 meters the computer was programmed to use the next shallower standard depth reached at both stations as the level of no motion.

The north-south current velocity components observed are plotted as a function of depth in Figs. 18 through 52. Portions of curves appearing on the right of the ordinate indicate a southward flowing current; those on the left a southward current. Depths are in meters, and velocities are given in centimeters per second.

An examination of the current velocity profiles shows that, in general, the greatest velocities and the greatest reversals in direction occur in the upper 200 meters.

During 21 and 22 September 1971 a southward flowing current was observed having a velocity on the order of

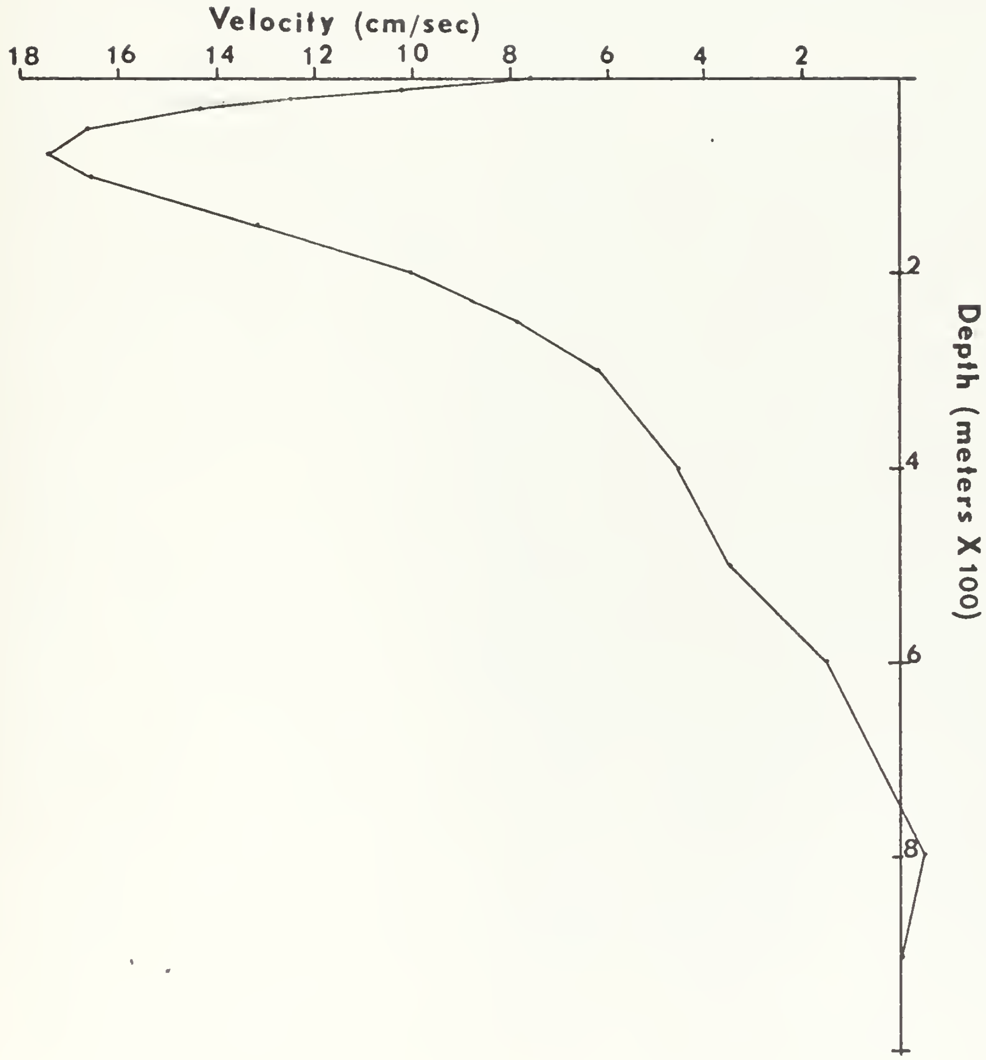

Fig 48. Representative current velocity profile between Stations 2 and 3 for September 1971. Southward transport is to the left of the ordinate.

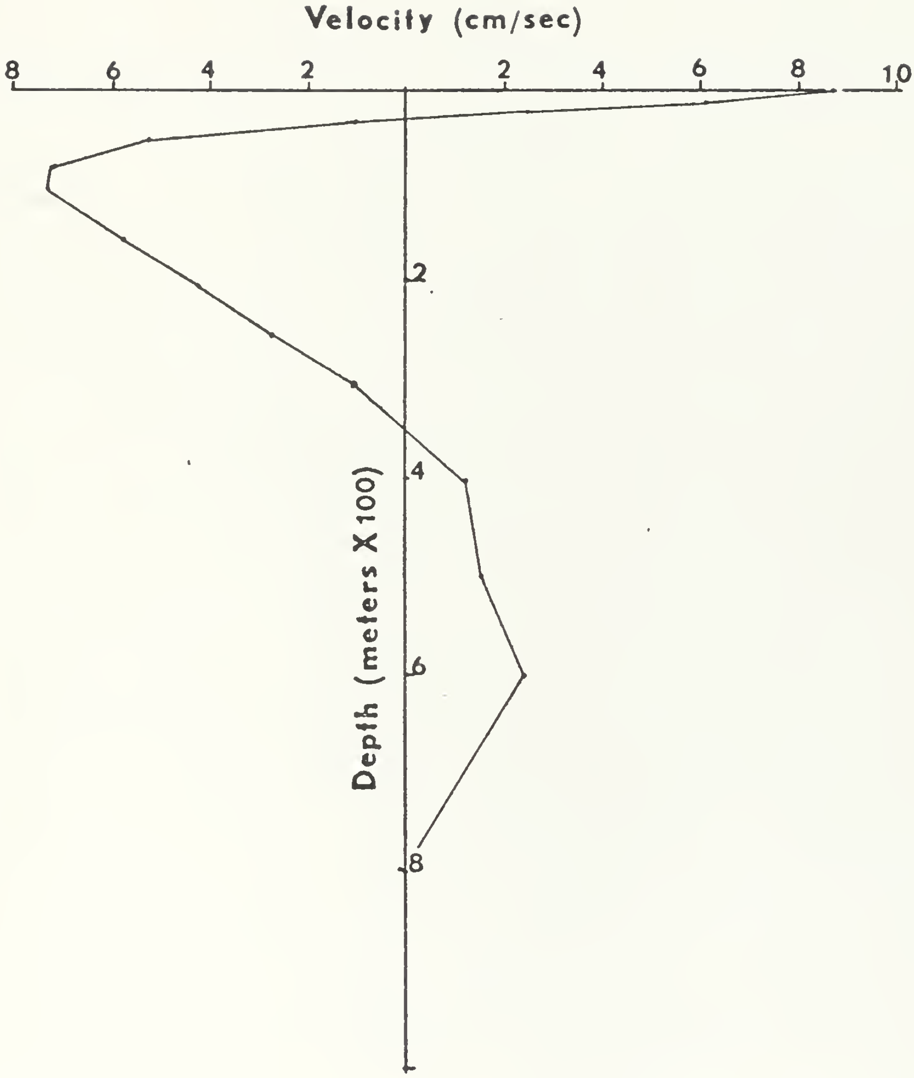

Fig 49. Representative current velocity profile between Stations 2 and 3 for October 1971. Northward transport is to the right of the ordinate.

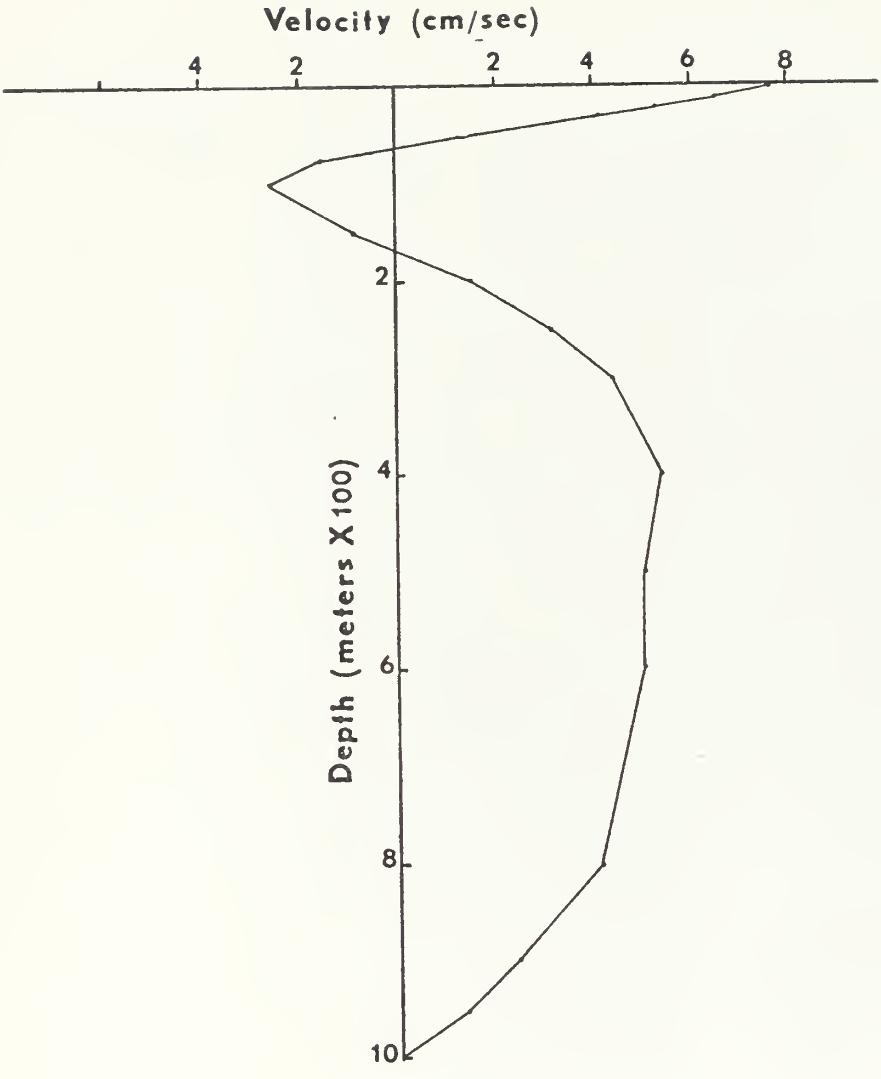

Fig 50. Representative current velcocity profile between Stations 2 and 3 for November 1971. Northward transport is to the right of the ordinate.

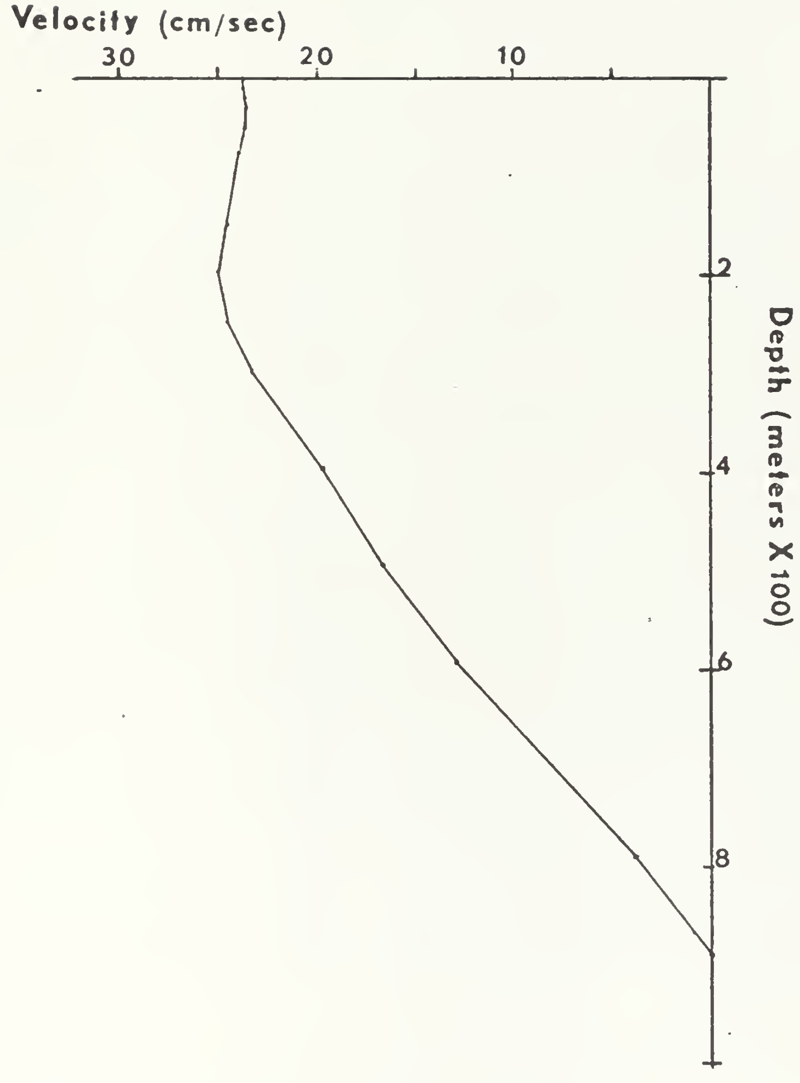

Fig 51. Current velocity profile between Stations 2 and 3 for 30 December 1971. Southward transport is indicated. Note change in velocity scale.

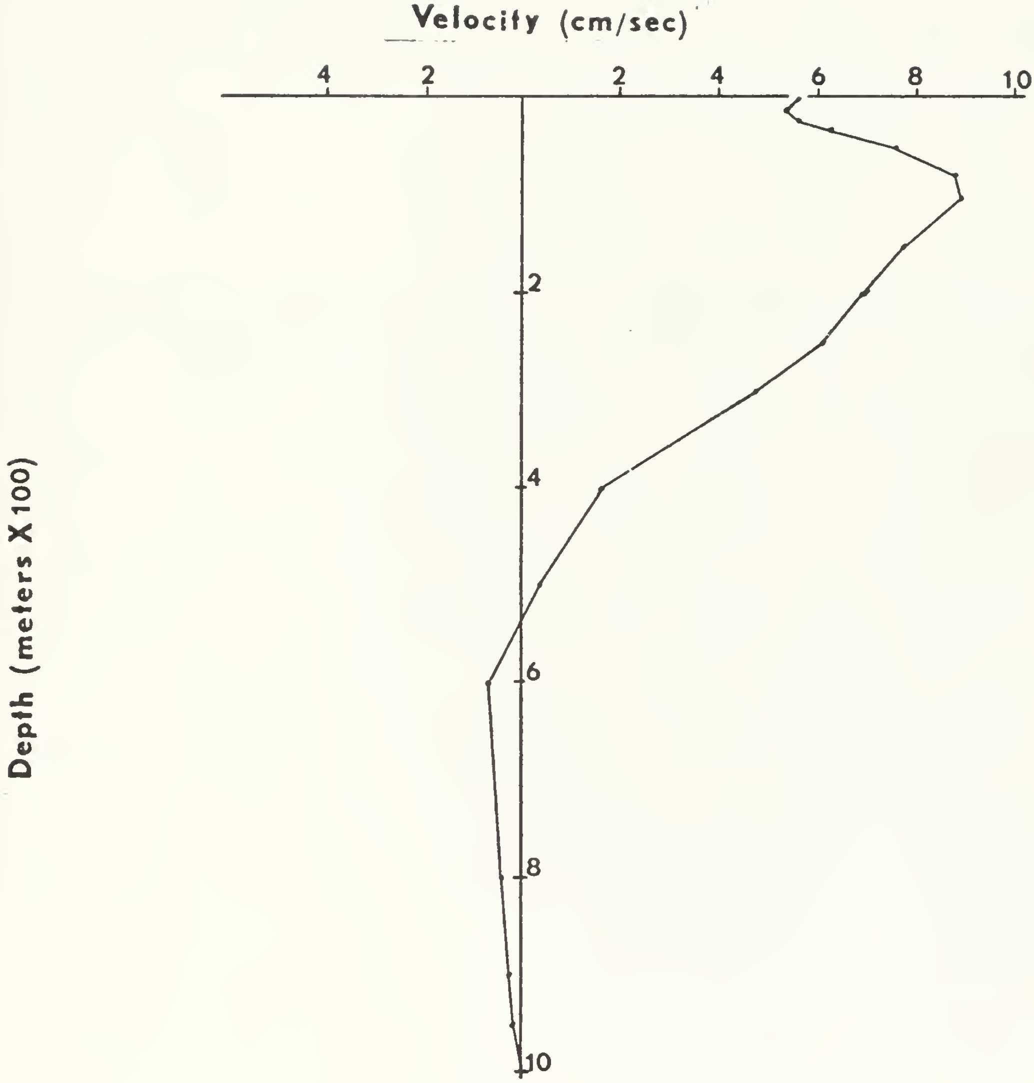

Fig 52. Representative current velocity profile between Stations 2 and 3 for January 1972. Northward transport is to right of the ordinate.

15 cm/sec (0.3 knot) at roughly 100 meters. On the 23rd, however, the calculations indicate a current having a velocity maximum of 60 cm/sec (1.15 knots) at a depth of about 100 meters. The mass transport perpendicular to the plane between the two stations increased from 0.255 to 1.633 Sverdrups. The 60 cm/sec velocity was the greatest observed during this study.

An interesting deep (northward) movement was indicated from 6 October 1971 through 24 November. The core of this flow was at a depth of about 700 meters, had a velocity of just less than 2 cm/sec, and was located between 500 meters and 850 meters on 6 October. On 14 October the flow was located between 350 and 800 meters with a maximum velocity of 2.4 cm/sec at 600 meters. A week later, on the 22nd, the flow was present from 260 meters to at least 950 meters with a velocity of 4.6 cm/sec at 500 meters. The steepness with which the curve for 22 October approaches the reference level implies that there was some movement at the assumed "level of no motion." Any flow existing at the reference level must be added to the geostrophic flow to obtain the absolute current. Velocities obtained by the geostrophic assumption are not absolute unless it is known that there is no motion at the reference level, but they are of value in making qualitative comparisons between observations.

The greatest strength observed for this current occurred on 19 November when it was found from 170 meters to 1,000

meters. It had a maximum velocity of 5.4 cm/sec at 400 meters. On 24 November 1971 the northward current was found between 575 and 1,000 meters with a maximum of 4.3 cm/sec at a depth of around 600 meters. From 24 November to 14 January no northward current was observed at any depth.

The time span during which the deep northward current was observed coincided with the October and November 1971 surge in upwelling. A southward transport was present above this northward current. The northward current was, presumably, a part of the Davidson Current underlying the California Current. However, the low vertical thermal gradient in the upper 50 to 100 meters during the Davidson Current Period was observed from the first part of November to the end of the study.

On 17 and 30 December a southward current only was observed between Stations 2 and 3, but on 14 and 21 January 1972 the transport perpendicular to the plane between the two stations was clearly to the north. While this current reversal was at first viewed with suspicion no error was found in the data or the calculations.

Inasmuch as the low thermal gradient in the upper 50 to 100 meters characteristic of the Davidson Current Period clearly existed in the bay during part of November and all of December and January, it was assumed that the Davidson Current was affecting Monterey Bay. The sporadic appearance

of the northward current in the current velocity profiles implies that the transport between Stations 2 and 3 does not fully represent the behavior of the Davidson Current. On the other hand it seems reasonable that the changing currents in the bay would be affected by the bottom topography to produce eddies which could divert or at least decrease the intensity of the Davidson Current in the vicinity of Stations 2 and 3 at the southern entrance to the bay.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Oceanographic data collected over a series of nine stations in Monterey Bay between 21 September 1971 and 28 January 1972 were compared with findings of earlier investigators. It was realized early in this research that the temperature characteristics of this body of water were unusual relative to long-term averages. Abnormally high sea-surface temperatures during the summer months decreased very rapidly in October 1971 to produce winter temperatures approximately 2°C cooler than climatology would have indicated.

Upwelling in August 1971 was extremely weak but was followed in October by an anomalously strong increase which interrupted the expected progression of oceanographic seasons in Monterey Bay. The Oceanic Period was little more than a brief interval between the Upwelling and Davidson Current Periods. While the low vertical thermal gradients characteristic of the Davidson Current were clearly evident in the bay, the onset of this regime appeared to be delayed by the upwelling.

Sverdrup et al. described the California Countercurrent as a wind-driven northward flowing current which was present along the coast at all times but was minimized at least in the surface layers by upwelling. This current has been described as existing along the West Coast of the United States from Baja California, to around latitude 55°N.

On the basis of north-south current observations made between Stations 2 and 3 certain points are raised by this investigator. If the Davidson Current does indeed flow along the coast it must move in meanders which cause it to migrate out of the immediate coastal waters. At times during this study it was not present. The northward stream observed at a depth of approximately 600 meters was not evident during the anomalous period of upwelling. After the upwelling it was not observed until the thermal structure characteristic of the Davidson Current was fully developed in Monterey Bay. A study of monthly mean sea-level atmospheric pressure charts showed low wind speeds and does not indicate the presence of a southerly wind component along the coast of California during this four-month time period. The low wind speeds and lack of wind steadiness coupled with the development of the northward current during the surge in upwelling have caused this researcher to doubt that the California Countercurrent is, in fact, a fully wind-driven current. Admittedly this doubt is based on only a brief observation during an unusual season.

A warm pool or tongue of water similar to that observed by Lammers was observed. The warm water persisted throughout this study. This warm tongue clearly followed the axis of the Monterey Canyon for several miles and was not restricted to the area at the head of the canyon (note the 10°C isothermal topography).

Throughout most of this study the surface layers at Station 3 were less saline and warmer than at Station 2 until

December when the temperature-salinity curves of both stations are similar. The similarity of T-S curves coincides with the Davidson Current Period in the bay, and it is concluded that when the water at Stations 2 and 3 became similar the Davidson Current had moved in toward the coast and influenced Monterey Bay.

One of the objectives of this study was to attempt to quantify the thermal gradient description of the Davidson Current Period in Monterey Bay. While, on the basis of this study, it was possible to assign a somewhat arbitrary value of -1°C per 100 meters for the upper 100 meters it is concluded that since this season exhibited such anomalous behavior it would be unwise to use this value to describe the regime in the future.

B. RECOMMENDATIONS

It is recommended that the bay study be continued on at least weekly intervals. The series of stations should be expanded to give coverage in the northwestern portion of the bay. As a result of the California Current eddies affecting the bay may exist here.

Whenever possible two or, preferably, three ships should make simultaneous parallel north-south transits from south of Pt. Sur to Pt. Ano Nuevo. The ships should be roughly ten miles apart and should conduct Nansen casts or STD casts simultaneously at no greater than ten-mile intervals along their tracks. The dynamic calculations performed on these

data should give a good estimate of the east-west and north-south currents affecting Monterey Bay.

At the earliest opportunity, buoys and towers should be used in coordinated studies with R/V ACANIA to make the observations more synoptic than is now possible.

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13. ABSTRACT

Nine oceanographic stations in Monterey Bay were occupied on at least weekly intervals from 21 September 1971 through 28 January 1972. During this period the three oceanic seasons described by previous investigators were observed. Measured thermal conditions were compared to previously derived long-term mean values. The magnitude of the short-period thermal fluctuations was comparable to that noted in earlier investigations. The changes in seasonal thermal structure were greater and more rapid than climatology implied. Unusually weak upwelling in August 1971 was followed in October by stronger than normal upwelling. This resulted in an interruption in the Oceanic Period and delayed the start of the Davidson Current regime in the bay.

The network of regularly occupied stations was more extensive than had been previously possible. Quasi-synoptic observations between two offshore stations indicated north-south geostrophic current velocity components on the order of 2 to 14 cm/sec.

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